THE UNIVERSITY OF ALBERTA

The Holocene Palaeoclimatic History of Pine Lake, Alberta.

by

Aileen Rhodes

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled The Holocene Palaeoclimatic History of Pine Lake, Alberta. submitted by Aileen Rhodes in partial fulfillment of the requirements for the degree of Masters of Science

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Abstract

Fossil pollen, plant macrofossils, and diatoms were extracted from two lake sediment cores from Pine Lake, Alberta (52°04'N;113°27'W) and provide clear evidence of Holocene climate change. This study is the first of its kind to incorporate these three indices into palaeoclimatic research at the southern boundary of the aspen parkland.

Picea pollen from the basal portion of core PLDC (Pine Lake deep core) provides evidence of a version of early boreal forest. More arid conditions are indicated by more open vegetation consisting of *Artemisia*. This is followed by grassland expansion caused by effects of either natural or aboriginal fires. A shift to conditions of the modern aspen parkland is suggested by the most recent fossil pollen consisting of high relative percentages of *Salix* and *Populus*. Superimposed on broad shifts in pollen taxa, derived from regional sources, are smaller scale disturbances such as fire, as reflected by the saw-toothed nature of the pollen data.

The aquatic macrofossil record registers clearly, local shoreline transgressions. Basal sediments of core PLLC (Pine Lake littoral core), dated at >8900 YBP, are devoid of macrofossils but are shortly followed by a deeper water interval, indicated by the presence of submergent and emergent plant taxa. This is succeeded by sediments containing both seeds and leaves of *Picea*, and charcoal, suggesting a reduction of water levels and an inward shoreline displacement. Successive sediments contain Betulaceae, followed by the submergent bryophyte *Drepanocladus aduncus*, suggesting a gradual increase in water levels despite continued mid-Holocene aridity, indicated by abundant macroscopic charcoal. As climate cooled and conditions became wetter, a significant shift to higher water levels occurred, as revealed by increases in the submergent macrophytes *Chara* and *Zannichellia*. This is interrupted by a period of water level reduction as registered by predominance of the emergent taxon *Scirpus* and by Labiatae. Modern conditions are established in the final interval as lake levels rise and *Chara* dominates again.

Planktonic diatoms from the basal sediments of core PLDC suggest that the lake basin began filling rapidly. Large peaks in planktonic diatoms possibly represent a deep water interval observed in the plant macrofossil record in core PLLC at 205-235cm. Indications of early to mid-Holocene aridity, resulting from maximum insolation are suggested by high diatom concentrations and the predominance of the tiny diatom, *Stephanodiscus parvus*, which

prospers during times of silica depletion, which is often associated with reduction of groundwater influx. A shift to the highly silicified taxa, *Aulacoseira granulata* and *Cyclotella bodanica* mark the increase of groundwater/surface runoff influence and the progression to cooler, wetter, modern climatic conditions. A predominance of the oligotrophic to mesotrophic diatom *Cyclotella bodanica* occurs in more recent sediments inspite of phosphorus loading. Lack of a more eutrophic dominant diatom is attributed to competition with blue green algae.

Although each of the three indices respond to environmental change on different temporal and spatial scales, all register mid-Holocene aridity and provide valuable climatic data.

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1.0 Introduction

1.1 Objectives:

Many studies have been carried out during the last thirty years in Alberta, that focus upon palaeoecological reconstructions of late-glacial and Holocene environments. Most of these have centered upon terrestrial vegetation history and associated climatic change (Lichti-Federovich, 1972; 1970; Luckman & Kearney, 1986; MacDonald, 1989; Ritchie, 1976; Vance, 1986; Vance *et al.*, 1983; Kearney & Luckman, 1987; Beaudoin & King, 1990; Hickman *et al.*, 1983; White & Mathews, 1986). Later investigations were broadened to include palaeolimnological proxy data including diatoms and pigments, and their responses to water level changes, production, and watershed stability (Hickman, 1987; Hickman & Klarer, 1981; Hickman & Schweger 1996; 1993; 1991; Hickman *et al.*, 1990; 1984; 1983; 1989). While plant macrofossils have provided additional evidence for vegetation reconstruction in studies focused on palynology (Kearney & Luckman; Luckman & Kearney,1986; 1987), few investigations utilizing plant macrofossils derived from an aquatic environment to reconstruct palaeoenvironmental change have been carried out (Vance *et al.*, 1992). This investigation is one of the first to incorporate pollen, diatoms, and plant macrofossils (including macroscopic charcoal) in a multidisciplinary study of palaeoclimatic change. The aim of this study is to demonstrate the sensitivity of diatoms and plant macrofossils from the sediments of Pine Lake, Alberta (52°04'N; 113°27'W) as indicators of palaeoclimatic change. Pollen will be analyzed to provide comparison to the regional terrestrial vegetation record. These three lines of evidence should prove complimentary and be incorporated into a multidisciplinary approach that strengthens interpretations of Holocene climate change.

There are a variety of palaeoenvironmental records in Alberta from the Rocky Mountain Foothills region (Beaudoin & King, 1990; Luckman & Kearney, 1986; Kearney & Luckman, 1987; Hickman & Schweger, 1991, 1993; Bear, 1989; Mac Donald, 1989) and the southern margin of the boreal forest (Hickman *et al.*, 1984; Hickman & Klarer, 1981; Vance *et al.*, 1983; Lichti-Federovich, 1972, 1970; Hickman & Schweger, 1996). The distribution of Alberta grasslands is determined by available moisture and therefore this region would likely provide a sensitive palaeoclimatic record. However, sites from this area are scarce due to lack of chronological control and incomplete records caused by the drying up of lakes during periods of aridity. Desiccated and cemented horizons also can create physical barriers that impede sediment coring. Vance *et al.*, (1992) examined a 7000 year record from shallow

Chappice Lake, Alberta (50°10'N; 110°22'W) and effectively determined lake-level changes based upon minerology, pollen, and plant macrofossil data. There is also a scarcity of palaeoecological investigations at sites located in the aspen parkland region, particularly along its southern margins (Hickman *et al.*, 1983). Similar to sites located on the southern perimeter of the boreal forest, sites along the southern margin of the aspen parkland should also register clear shifts in ecozone boundaries sensitively. Lake sediment records from the parkland region would also be less likely to have problems associated with desiccated and cemented horizons, providing more complete records than those of grassland regions. Therefore, this study also aims to demonstrate the sensitivity of southern parkland sites and begin to fill in the gap of palaeoenvironmental records for this region.

1.2 Palaeoecology

Palaeoecology is the study of relationships between past organisms and their environment or more generally, the ecology of the past (Birks & Birks, 1980). More precisely, palaeoecology is the study of individuals, populations, and communities of organisms that lived in the past and their interactions with, and dynamic responses to changing environments (Delcourt & Delcourt, 1991). The purpose of studying former plant and animal communities and their changes over time is to reach a higher understanding of the history of development, structure and function of modern ecosystems (Delcourt & Delcourt, 1991). Palaeoecology and ecology have similar objectives and may assume the same biological principles but differ in their approach because it is impossible to observe past ecosystems directly. Therefore, biotic and abiotic ecosystem components must be inferred from the organisms which become fossilized, denying those which are not preserved. For this reason indicator species may be useful. Certain taxa have narrow enough known ecological tolerances that make their presence diagnostic of a particular environmental condition. Still, a particular fossil assemblage may not be a true snapshot of the past because of processes such as transportation, redeposition, and diagenesis. In a particular environment, fossils may be modified prior to deposition. For example, salinity, and pH can lead to the dissolution of siliceous valves of diatoms, and physical processes such as wave action can damage pollen, plant macrofossils, and diatoms. Higher rates of sediment deposition are experienced near inflows or centers of conical basins. Sediment focusing occurs when water currents and gravity move fine material from edges to deeper areas. Evidence from one location may be transported to another by way of streams or

springs leading to artificial mixing of taxa from different communities living concurrently within one environment. Moreover, fossils may be irregularly redistributed by water movements. Heavier particles may not be as susceptible to redistribution as lighter ones which settle more slowly and are, therefore, more evenly redistributed. Redeposition may occur when water levels fluctuate, resulting in the erosion of older material and its redeposition in to a lake. Conversely, younger material may be mixed with older material on land or in aquatic systems by burrowing animals or moose. Therefore, care must be taken when choosing a study site to minimize taphonomic factors. An ideal coring site for diatoms and pollen might then be in the deepest portion of a gradually sloping lake basin, away from inlets where burrowing animals and moose are absent and redeposition and mixing are minimal. Different types of sedimentary environments have varying potentials for the preservation of organic remains. Obviously, preservation is most likely if upon death, the organisms are buried immediately. Deposition of fine grained materials such as silt and clay can provide a protective seal that inhibits further microbial decomposition. In tropical and temperate regions, fossil assemblages rarely persist on upland surfaces that are subject to erosion or to seasonal wet-dry or cold-warm cycles (Delcourt & Delcourt, 1991). In boreal or arctic zones, perennially frozen ground provides a more constant environment for preservation. Optimal environments for fossil preservation are freshwater lakes, bogs, swamps, brackish estuaries, and ocean basins (Delcourt & Delcourt, 1991). Hence, organisms derived from aquatic or near aquatic habitats are more consistently represented in the fossil record than those from terrestrial habitats (Delcourt & Delcourt, 1991).

1.3 Climate

To most, climate is the normal weather pattern for a place or region. Although a region may have considerable variation, precipitation and temperature will fall within a certain range. In actuality, climate is created by the redistribution of the sun's energy which heats the earth unevenly. This imbalance leads to the redistribution of heat and moisture from one area of the globe to another. Local and regional climates are affected by latitude, altitude, topography, and proximity to local water bodies.

The interval of 12 000 - 6000 YBP is considered to be a period of general aridity and warmer conditions in the northern hemisphere. According to the Milankovitch hypothesis, changes in the earth-sun orbital geometry cause variations in the seasonal and latitudinal

distribution of solar radiation. Compared to the present, seasonality of solar radiation was considerably greater from approximately 12 - 6 ka, reaching a maximum at about 9 ka, when solar radiation was greatest in the northern summer (Kutzbach & Webb III, *in* Wright *et al.*, 1993). Summer insolation was approximately 8% greater than present, and winter insolation was less (Kutzbach & Webb III, *in* Wright *et al.*, 1993). Although there was a greater seasonality in continental interiors during this interval, with estimated summer temperature increases of 5°C warmer than present at 9 ka (generally 2-4°C increase during 12-6 ka) and colder winters, the annual-average temperature is proposed to have changed little (Kutzbach & Webb III, *in* Wright *et al.*, 1993). This is registered in several Alberta lake records (Table 1.) (Hickman & Schweger, 1996; Hickman & Schweger, 1993; Hickman & Schweger, 1991; Hickman *et al.*, 1984; Vance *et al.*, 1992). Pollen records from sites located at the southern perimeter of the boreal forest are sensitive and register early to mid-Holocene warming as northern shifts in grassland (Hickman *et al.*, 1993; Hickman & Schweger, 1996; Lichti-Federovich, 1970, 1972; Vance *et al.*, 1983; Ritchie, 1976).

1.4 Water levels as indicators of palaeoclimatic change

Evidence of water level fluctuations in particularly closed lakes is considered to be a sensitive indicator of palaeoclimatic change and is therefore a possible determiner of future climatic fluctuations (Mason, Guzkowska, Rapley, & Street-Perrott, 1994). Vegetation and climate are hypothesized to have altered very little during the last 4-5 ka (Lichti-Federovich, 1970; Ritchie, 1984; Vance *et al.*, 1983; Hickman *et al.*, 1984; White & Mathews, 1986; Schweger & Hickman, 1989). However, compared to terrestrial ecosystems, several lakes in Alberta register significant changes during the last 4-5 ka (Forbes & Hickman, 1981; Hickman *et al.*, 1984; Hickman, 1987; Hickman *et al.*, 1990). The area of a closed lake basin represents an equilibrium between runoff from the catchment and the water deficit over the lake surface (Harrison & Digerfeldt, 1993). The response of lakes with outflow streams or rivers to climatic fluctuations may be more complex and somewhat dampened by the existence of an outlet.

Table 1. Approximate times of Holocene aridity found in Alberta lake records

Site	Location	Holocene aridity	Reference
Maligne Range	Alpine	8800-5200 YBP (7300-7400 moist)	Luckman & Kearney, 1986.
Fairfax L. (52°58'N;116°34'W)	Subalpine	11 255-7000 YBP	Hickman & Schweger, 1991.
Goldeye L. (52°27'N;116°12'W)	Montane Boreal Forest	14 500-10 400 YBP (12 500-11 500 moist)	Hickman & Schweger, 1993.
Wabamun L. (53°35'N;114°30'W)	Transitional Forest	>6600-4000 YBP	Hickman *et al.*, 1984.
Lofty L (54°44'N;112°29'W)	Boreal Forest	9200-6000YBP	Lichti-Federovich, 1970.
Moore L. (54°30'N;110°30'W)	Boreal Forest	9200-5900 YBP (9100-8400 moist)	Hickman & Schweger, 1993.
Eaglenest L. (57°46'N;112°06W)	Boreal Forest	11 800-9000 YBP	Vance, 1986.
Toboggan L (50°46'N;114°36'W)	Subalpine	8000-5000 YBP	MacDonald, 1989.
Buffalo L. (53°15'N;112°51'W)	Aspen Parkland	6700-3175 YBP	Hickman *et al.*, 1983
Chappice L. (50°10'N;110°22'W)	Northern mixed grass	7300-4400	Vance *et al.*, 1992.

However, Harrison & Digerfeldt, (1993) demonstrate from remnant high shorelines around lakes with current outflow, that this dampening is only partly effective. Basin morphometry plays a large role in determining how water level fluctuations are expressed. A lake with a steep shoreline will undergo a significant change in depth with a minor alteration in water surface area, whereas a lake with a more gently sloping shoreline requires a large change in area to register a decrease in shoreline. Moreover, the slope of the shoreline may vary for the same lake at different times. A lake may occupy a steep basin at lower water phases but may spill over onto a more gradually sloping littoral area during high water level intervals. Climate related lake level changes can be caused by seasonal changes of level, which can vary among lakes in pattern and amplitude but are repetitive. Also important are irregular, short-term fluctuations, lasting several years and longer term trends toward higher or lower levels. Successional decreases in depth also occur due to infilling of the basin with sediment. In this case, effects of the decrease in volume may be the same as if water levels actually decreased but the level of the water surface does not truly change. Also, succession is unidirectional and leads eventually to extinction of the lake. True fluctuations in water level involve expansion and contraction as well as extinction and rebirth.

1.5 Monitoring palaeoecological changes

1.5.1 Size-fraction analysis

A vast variety of components in lake sediments can be used to monitor palaeoecological changes. The sediments themselves may provide information of lake level fluctuations. Well-sorted sands generally correspond to beach or nearshore deposits, while laminated sediments are derived from very deep water. If a lake has varied in surface area, then the ratio of sand, silt, and clay that reached the core site should also have varied (Richardson, 1969). In general, a higher ratio of coarse to fine detrital matter should have been deposited during phases of lower water level when the coring site was more proximal. If the lake level was higher, suspended detrital material would have to be carried further into the lake to reach the core site, resulting in higher proportions of lighter clay compared to heavier silts and sands. However, interpretation may be complicated by the fact that clays and feldspars in some sediments, particularly alkaline or saline lakes may be destroyed or formed in situ by authigenic processes (Richardson, 1969). Coarse-grained material may also be deposited where erosion of the catchment occurs after a local disturbance such as a fire. Also, the entrance point of a stream

may have changed in relation to the core site, exposing the sediments to different degrees of water movement and altering the sediment size-fraction ratio. Alternatively, a decrease in water level may have resulted in the transition from deeper turbulent open water to shallower, quiet water, which although more proximal to the core site, would receive less coarse material than the former giving the opposite results of what would be expected. The shallow, littoral zone of lakes is liable to undergo intense sediment mixing, particularily by wave action (Hilton, 1985). Therefore high resolution studies of sediments from this part of the lake basin are impossible. Furthermore, factors affecting erosion into the lake such as changes in rainfall, and/or vegetation could alter the size fraction of material reaching the core site independent of any change or lack of change in lake level.

1.5.2 Sedimentary chemical evidence

Closed lakes vary chemically with water level changes, and evaporite salts may be deposited during low water periods. As a closed lake shrinks by evaporation, calcium carbonate, which is least soluble, is precipitated first, followed by magnesium carbonate, dolomite ($CaMg(CO_3)_2$), and finally, gypsum ($CaSO_4.2H_2O$) (Richardson, 1969). Difficulties in interpretation of sediment chemistry are inherent due to the fact that the variation of calcium carbonate precipitation is more often biologically produced via photosynthesis than by evaporation (Richardson, 1969).

Mineralogical and paleobotanical remains were utilized effectively by Vance *et al.*, (1992) in Chappice Lake (50°10'N; 110°22'W) to interpret drought intervals. Shallow water intervals thought to represent the Hypsithermal (9000-6000 YBP) and Medieval Warm Period (950 - 1250 A.D.) are indicated in the sediment record by the presence of carbonate rich laminae containing saline tolerant plant taxa. The presence of laminae themselves suggest high salinity because benthic organisms capable of disrupting the laminae are less likely to be present when concentrations of dissolved solids are high. High water intervals are represented by massive, silicate rich sediments with lower amounts of halophytes.

Variations of iron and manganese, or of the ratio of these elements, and of pyrite spherules may be an indicator of intermittent anaerobiosis (Richardson, 1969). Anaerobic conditions can be an indication of higher water depths but can also occur in shallow lakes under winter ice-cover, or in hypereutrophic conditions. Therefore, changing redox conditions are not necessarily an indication of water level changes and one should use evidence indicating

this with caution.

The application of biochemical indices in inferring past lake levels is limited. Organic residues in sediments may be evolved from a variety of organisms, and it is difficult to prescribe a specific ecological meaning to information obtained. Even algal pigments only give an idea of what algal group is present and if it is established that a particular group has fluctuated, it may be due to changes in trophic conditions which does not necessarily indicate any water level change whatsoever. Richardson, (1969) suggests that in small-to-moderate size lakes, high variability of almost any parameter, such as organic content, detrital minerals, exchangeable ions or dominant diatoms can be an indication of fluctuation of water levels. In all lakes, water levels fluctuate constantly but volume changes in a lake that stood at a high level would be less apparent than that of a lake in a shallow phase where seasonal and annual fluctuations of climate would have a greater proportional impact on lake volume.

1.5.3 Biostratigraphical data

Biostratigraphic data including aquatic pollen, plant macrofossils, and diatoms (as well as molluscs and ostracodes, not discussed here) provide valuable information about water-level changes. The depth at which an individual species is found may vary from lake to lake depending upon water transparency, degree of exposure, and the type of substrate (Wetzel, 1970). However, at one particular site, distribution is determined mainly by water depth, leading to a characteristic zonation of emergent, floating leaved, and submerged macrophytes, from the shore towards the center of the lake. Changes in relative abundance of these types of fossil organisms in the sediment record can register horizontal displacements of the littoral zone relative to the coring site. It is important to note that some types of stratigraphic changes have more than one explanation. Changes in composition of aquatic vegetation may be due to water level changes or a change in water quality.

Interpretations of data can be strengthened by the use of multiple lines of evidence and seeking a consensus among all available information. The following takes a closer look at the types of fossils pertaining to this study and their advantages and limitations.

1.5.3.1 Pollen

Of all biostratigraphic methods, pollen is the most commonly used and has a long history of use extending from the beginning of this century when Scandinavian botanists, lead by Lennart von Post began to make quantitative counts of pollen from peat (Moore *et al.*, 1990). Pollen is especially useful since its sporopollenin containing cell walls are very resistant to decay. Like diatoms, pollen morphology is recognizable often to species level, although many are only discernible to genus or family level. Pollen analysis has made it possible to reconstruct the floral history of western Canada, although incomplete, which has lead to greater knowledge of palaeoclimates and vegetational responses to climate change. As with diatoms and macrofossils, interpretation of pollen data requires several assumptions. Foremost, is the assumption that the frequency of a particular pollen type within an assemblage directly reflects the abundance of that taxon in the surrounding area. Also, long distance transport, dispersal efficiency, and production of pollen are important considerations. According to Ritchie, (1984), *Alnus*, a prolific pollen producer, comprises less than 10% of the vascular vegetation cover in the tundra and forest-tundra region but contributes 50 - 70% of the modern pollen spectra of these vegetation zones including sites far beyond the modern range of *Alnus*. Conversely, *Larix larcina* which is a common boreal species, is seldom encountered in modern and fossil spectra (Ritchie, 1987). Many plants are able to reproduce vegetatively for long periods of time until appropriate conditions for flowering are available, therefore, a population of a particular species may exist leaving no pollen record. The type and amount of physical obstacles that anemophilous (wind dispersed) pollen encounters also affects what pollen reaches lake sediments. Trees and shrubs can act as filters for pollen moving through the air. This capture rate is enhanced by increased wind speeds (Moore *et al.*, 1990). Therefore, species which flower early before leaves emerge may be dispersed beyond any existing canopy. When expressing data with relative percentages, as in this study, it must be observed that the abundance of any particular pollen type will be influenced by the abundance of other types. Often pollen is only identifiable to genus or family level. This lack of specificity can make ecological inferences challenging, as in the case of grasses. Members of the Poaceae family inhabit a range of environments such as dry and moist alpine and montane areas, moist and dry prairie, open woodlands, marshes, and shallow water. Indicator taxa such as *Amorpha*, *Petalostemum*, Ambrosieae, and *Phlox hoodii* make it possible to recognize mid-postglacial grassland assemblages from the Western Interior (Ritchie, 1976).

1.5.3.2 Plant macrofossils

The term "plant macrofossil" is used to describe any identifiable plant fossil recovered from sediments which can be seen with the naked eye or with the aid of low power magnification. Most often this includes seeds, fruits, charophyte gyrogonites (oospores), and charcoal as they are well preserved in sediments. Also useful are pieces of wood, leaves (cuticles as well), rhizomes, and bryophyte leaves. Plant macrofossils are valuable because they are often identifiable to species level, compared to pollen which is often only identifiable to generic or family level. Also, many aquatic plants produce little (*Potamogeton*) or no pollen at all (bryophytes and charophyte algae) but are prodigious seed and spore producers. Moreover because of their relatively large size, macrofossils are not likely to be transported very far from parent plants. In lake sediments, macrofossils of aquatic plants may be deposited quite proximally but these sediments may also contain macrofossils from nearby aquatic and lake margin communities (Birks & Birks, 1980). In general, macrofossil assemblages are representative of local communities and are too narrowly focused to be of value in the reconstruction of upland vegetation. Since samples taken from different shoreline localities may differ considerably, it is not even possible to reconstruct the shoreline vegetation history for an entire lake from macrofossil data from a single core. Therefore, macrofossils are most useful in wetland and lakeshore habitats while pollen represents a more regional picture. This localized nature of macrofossil evidence makes them useful for reconstructing shoreline movements at a particular location. Aquatic plants rely heavily upon vegetative reproduction, therefore macrofossils are produced in relatively small numbers. Consequently, a considerable amount of sediment must be extracted, and sieved for macrofossils, which can be time consuming. In addition, their proximal dispersal may lead to sharp fluctuations in numbers of macrofossils per unit sediment if vegetation has changed or a water current happens to transport seeds.

Difficulties may be encountered in the identification of fossil seeds or fruits when immature seeds are aborted, or where epidermal cells exhibiting characteristic ornamentation are sloughed off. When interpreting fossil macrofossil assemblages it is beneficial to know the rate of macrofossil production of the plant and how this is affected by environmental factors and the plant's life cycle. For example, will a stand of particularly young plants produce abundant seeds or will they put more energy into growth of vegetative organs? In what portion

of the growing season are seeds produced? The submersed hydrophyte *Ruppia*, often used as an indicator of saline conditions, produces a higher number of flowering plants with increasing salinity (Husband & Hickman, 1985). Do the seeds require a dormant period or do they germinate quickly? Seeds which germinate quickly obviously would not make good candidates for preservation. Are there animals that consume the particular seeds or fruits? Also, what is the dispersal strategy of the seeds (i.e.) wind, water, or animal? Are the seeds big, small, flat, or round? Although much of this information may not be available, these factors could have a large effect upon the final destination of the seeds. According to Birks & Birks, (1980), interpretation of macrofossil data as with fossil diatom and pollen data is complex but the assumption that the numbers of macrofossils found is proportional to the organism in its original environment seems to be generally upheld. However, Jackson, (1986) *in* Ritchie.(1987) is less optimistic and points out that macrofossil assemblages do not provide an unbiased sample of watershed vegetation. Some forest taxa such as maples, beech, and mountain ash are extremely rare in surface macrofossil assemblages even though they may be abundant in watershed vegetation. Alternatively, conifers and birches are overrepresented.

Similar to terrestrial communities, aquatic communities undergo changes over years, centuries or millennia. Environmental changes such as geology, climate, and changes induced by the presence of the plants themselves cause a replacement and succession of species to ones that are better adapted to the present conditions. Results of long term changes such as geological processes of weathering, erosion, and deposition, are sometimes superimposed upon more frequent short term changes caused by temporary disturbances such as flooding, fires, or land clearing.

Few studies have been done utilizing macrofossils to uncover palaeocecological information. Vance et al., (1992) used both sediment mineralogy and macrofossils to interpret past variation of water levels of a shallow, saline lake in Alberta. Both macrofossils and pollen of Chenopodiaceae and *Ruppia* were used to infer pronounced seasonal water fluctuations and high salinity respectively. High water levels were inferred from *Chara* oogonia. As previously revealed, *Ruppia* is a saline indicator species that thrives in saline (10-230 g/L), shallow water and produces numerous pollen and seeds near the upper limits of its salinity range (Hammer *et al.*, 1988). Several sites in Alberta register evaporative stress with the presence of pollen and macrofossils of the submersed hydrophyte, *Ruppia*. Wabamun, Moore, Goldeye and Eaglenest lakes, and Lake Isle do not presently have *Ruppia* growing in

them but pollen records show *Ruppia* populations were reproducing in the past, presumably during periods of salinity, when climate was arid. This interpretation is confirmed by diatom records (Hickman *et al.*, 1984; Hickman & Schweger, 1996; Hickman & Schweger, 1993; Schweger & Hickman 1989; Vance, 1986). Buffalo Lake presently contains *Ruppia* but possessed significantly higher populations, during mid-Holocene, as indicated by increases in pollen percentages (Hickman *et al.*, 1983).

1.5.3.3 Diatoms

Diatoms are unicellular algae, although sometimes existing in pseudofilamentous or colonial aggregations. They date back to the Cretaceous and are distributed in both freshwater and marine environments as well as terrestrial habitats where quite often only periodic moisture is available. A unique feature of these algae is their beautifully sculptured cell wall, consisting of pectic substances impregnated with opaline silica. These siliceous walls preserve very well in lake sediments and diatom taxonomy is based upon their elaborate ornamentation. The morphology of many fossil species is identical to extant species, making long term ecological inferences possible. Diatoms live in two main types of communities, benthic (forms associated with a substratum) and planktonic (within the water column). Many benthic taxa can be differentiated into epipelic (those living upon the submerged sediments), and those attached to a substratum, including epilithic (rocks), and epiphytic (plants and other algae). Therefore, if a certain community dominates a particular fossil assemblage, information about water level may be revealed. Shifts from benthic forms to planktonic forms may be attributed to rises in water levels, as in the diatom record of Fairfax Lake (52°58'N; 116°34'W) where shifts from the planktonic taxon, *Stephanodiscus niagarae*, to a predominance of the benthic form, *Staurosira construens v. venter*, mark the beginning of mid-Holocene aridity (Hickman & Schweger, 1991). Diatoms can possess distinct ecological tolerances making them very useful palaeoecological indicators. Some are characteristic of nutrient status, others are characteristic of pH, salinity,light levels or water clarity. A diatom that is indicative of extremely eutrophic conditions and found in the fossil record of Alberta lakes is *Aulacoseira granulata*, found in sediments of Lake Wabamun and Baptiste Lake (Hickman *et al.*, 1984; Hickman *et al.*, 1990). Diatom taxa indicative of saline environments have proven valuable in the determination of periods of increased aridity. The paleoenvironmental history of Moore Lake, Alberta (54°30'N;110°30'W), shows a transition from freshwater to saline conditions by

the demise of freshwater diatoms such as *Stephanodiscus hantzschii* and *Fragilaria crotonensis* (11 600 - 9600 YBP) and the replacement of these with saline indicator taxa such as *Chaetoceros* and *Cyclotella caspia* (9600 - 5800 YBP) (Hickman & Schweger, 1996). The sediment record of Medicine Lake, South Dakota, similarly shows clear evidence of salinity change. Early (11 100 - 9260 YBP) assemblages are dominated by freshwater taxa such as *Stephanodiscus parvus*, however, from 9260 - 6500 YBP evidence for the lake becoming permanently saline is provided by the saline indicator taxa, *Cyclotella caspia*, *C. quillensis*, and *Chaetoceros* cysts (Radle *et al.*, 1989).

The abundance and succession of planktonic diatoms is governed by seasonal changes in nutrients (mainly silica and phosphorus), light levels, and turbulence (Bradbury,& Dieterich-Rurup, 1993). Many Alberta lakes, such as Pine Lake stratify, thaw in April or May and have complete water circulation, while thermal stratification develops in June. Stratification then weakens and thermocline deepens with cooler temperatures in September and October as circulation again commences in November until the lake freezes over and inverse stratification is established. During periods of summer and winter stratification, hypolimnetic oxygen becomes depleted and anoxic conditions occur below the thermocline. This environment is conducive to decomposition of organic matter which is broken down to yield phosphorous and nitrogen which are redistributed to the epilimnion during periods of stratification breakdown where they become available to algae. The turbulence accompanying circulation helps to suspend phytoplankton in the photic zone where photosynthesis occurs. Higher irradiance levels in the spring often produce larger spring blooms than those which occur in the fall. Silica, which is required for diatom growth is derived from the hypolimnion where sedimented diatom valves partially dissolve and from groundwater influx and surface runoff (Bradbury & Dieterich-Rurup, 1993). Diatom productivity and succession are closely regulated by climatic factors which control length and depth of circulation and nutrient recharge from ground water. Nutrient accumulation in the hypolimnion is partially directed by the length of periods of stratification. Silica:Phosporous ratios are a major influence in diatom production and different combinations of seasonal climate can affect these ratios, therefore, understanding climatic and limnological factors that affect these nutrients is essential for palaeoecological interpretation of diatom floras. This is illustrated in the Holocene diatom record from Elk Lake, Minnesota where alternations of *Fragilaria crotonensis* and *Stephanodiscus minutulus* represent shifts in limnological conditions under subtle climatic control (Bradbury & Dieterich-

Rurup, 1993). *Fragilaria crotonensis* blooms during summer and early fall at high Si:P ratios. *Stephanodiscus minutulus* appears during early spring circulation when phosphorus is abundant and is therefore, more prevalent when Si:P ratios are low. According to the model, dominance of *Stephanodiscus minutulus* implies early, mild springs and/or cooler summers, therefore extended spring circulation, as well as reductions in late winter and early spring precipitation. Shifts toward *Fragilaria crotonensis* are interpreted as reductions in spring circulation and/or increased silica influx due to increased precipitation. However, as with most ecological puzzles, the scenario can be complicated by other factors such as the presence of cyanobacteria which could compete with phosphorus-loving diatoms. Cyanobacteria are also more proficient at remaining buoyant than diatoms. These may sink beneath the photic zone during periods of reduced turbulence. In addition, the blue-green alga *Oscillatoria* is known to inhibit diatom growth through allelopathy (Keating, 1978) and exclude diatom species through nutrient competition (Fritz, 1989). As with other types of palaeoecological indicators, certain conditions lead to better preservation than others, therefore, problems associated with the use of diatoms in this kind of study must be recognized. Preservation of diatoms is in general, very good however some discrimination occurs. Diatom frustules may be chemically and/or physically eroded and fragmented. Fragmentation of certain elongate, delicate forms such as *Synedra* and *Asterionella* may occur. These are susceptible to abrasion with inorganic particles or in invertebrate guts, and therefore may be redissolved (Moss, 1993). Very thin-walled taxa such as *Rhizosolenia* may not be preserved at all. Variation in ornamentation of a single species due to shifts in dissolved silica levels may lead to difficulties in identification. Additional mechanical degradation may occur in shallow, well mixed lakes through resuspension and redistribution within the lake. Dissolution often occurs in very alkaline and saline waters. Because of differential preservation, any given fossil assemblage cannot be viewed as a complete snapshot in time.

1.6 Chronological control

1.6.1 Radiocarbon dating

Methods of radiocarbon dating techniques were first established by Libby, (1955). Since then techniques have advanced with the development of accelerator mass spectrometry (A.M.S.) dating. This dating technique relies upon the fact that unstable, radioactive ^{14}C is formed in the upper atmosphere by bombardment of ^{14}N by cosmic radiation. The ^{14}C is then

oxidized to CO_2 which is incorporated into terrestrial plants through photosynthesis and subsequently enters the rest of the food chain. Once an organism dies, ^{14}C uptake ceases and the isotope begins to decay at a particular rate, known as a half-life. Half-life is the amount of time required for the decay of half of the original content, which in the case of ^{14}C, is 5730±40 years (Linick *et al.*, 1989). If the proportions of ^{13}C:^{12}C:^{14}C are assumed to have remained constant in the atmosphere through time, one can measure the concentration of ^{14}C remaining in a sample and determine the length of time since the plant or animal died. In the past, researchers have had to rely upon detection of beta particle emissions created during decay. This requires 0.5-10 g of carbon and often more than twice that amount is required (Linick *et al.*, 1989). A.M.S. dating involves the counting of ^{14}C atoms directly, requires only 1 mg of carbon after cleaning, and chemical treatment and has an accuracy of ±50 years (Linick *et al.*, 1989). Both A.M.S. and conventional decay counting methods have about the same age limit of 50 ka BP. In lakes where groundwater is in contact with carbonaceous rocks which have no ^{14}C content, the ^{14}C:C ratio will be diluted, resulting in an older apparent age of samples which have derived their carbon from that water. Plants which grow below water and derive their carbon from the water, such as aquatic mosses, algae, and submerged vascular plants will all produce erroneously old dates in lakes with reservoir deficiencies in ^{14}C (MacDonald *et al.*, 1991). In contrast, emergent aquatics such as *Typha*, *Scirpus*, and *Carex* all derive CO_2 from the atmosphere, hence give more reliable dates (MacDonald *et al.*, 1991). Therefore, A.M.S. has an advantage in that samples of terrestrial origin such as seeds, leaves, wood, or charcoal which are quite small can be utilized. It should be observed that natural and anthropogenic variations in ^{14}C levels modify the assumption that carbon ratios remain constant. Material derived from 1850 and 1954 should be avoided due to ^{12}C enrichment caused by the burning of fossil fuels, which dilutes the ^{14}C concentration and gives erroneously old ages. Similarly, materials formed since 1954 show erroneously young dates due to detonation of nuclear weapons and resultant release of ^{14}C. Analysis of radiocarbon content of known-age tree rings from the last 9 ka, have lead to knowledge that there have been variations in the atmosphere's ^{14}C due to changes in the strength of the earth's magnetic field, (altering the cosmic ray flux) and solar modulation of the cosmic ray flux (Williams, M.A.J. *et al.*, 1993). Therefore a calibration curve for most of the Holocene has been established, allowing for correction of the radiocarbon time scale (Stuiver & Pearson, 1986).

1.6.2 Tephra analysis

Volcanic ash layers, also known as tephra layers, are important chronological markers. Mazama tephra is an air-fall deposit that resulted from the eruption of Mount Mazama, whose vent source is the Crater Lake caldera in Oregon. Mazama tephra has a widespread distribution and is found in several northwestern states as well as British Columbia, Alberta, and Saskatchewan. The tephra is well dated and dates range from 6600 to 7000 YBP (Sarna-Wojcicki *et al.*, 1983). The date commonly cited in recent literature and applied to this study is 6845 ± 50 YBP (Bacon, 1983). Distinguishing a tephra can be accomplished best by grain-discrete methods, so that contamination is minimal (Westgate & Gorton, 1981). Major elemental geochemistry of glass and iron titanium oxides are determined with an electron microprobe. Western Canadian tephras are commonly distinguished from each other by plotting a ternary diagram of the elements potassium, calcium, and iron (Reasoner & Healy, 1986; White & Osborn, 1992; Westgate & Evans, 1978).

2.0 Study Site

2.1 Description of lake and catchment

Pine Lake (52°04'N; 113°27'W), (Fig. 1) is a serpentine shaped freshwater lake located in a glacial meltwater channel in Alberta's aspen parkland ecoregion, 35 km southeast of the city of Red Deer, Alberta. It has a maximum length of 6.5 km and a maximum width of 0.8 km (Mitchell & Prepas, 1990). The lake has a surface area of 3.89 km^2 and a maximum depth of 12.2m in its south basin (Mitchell & Prepas, 1990). Groundwater flows SW to NE for the majority of the lake except for the most southern portion where groundwater flow enters from both the SW and the NE (Steve Clare, pers. comm.). Pine Lake is fed by several intermittent streams, which mostly enter at the northern end of the lake. Ghostpine Creek, flows out from the south end into Threehills Creek which flows into the Red Deer River near Drumheller (Mitchell & Prepas, 1990). The underlying bedrock of Pine Lake is the Paskapoo Formation, consisting of sandstone, siltstone, mudstone, limestone, coal and tuffbeds (Mitchell & Prepas, 1990). Agriculture is extensive with fifty percent of Pine Lake's basin under cultivation, while recreational development occupies over one percent of lake shores (Mitchell & Prepas, 1990). South facing areas of the gently rolling topography of the basin contain predominantly *Festuca scabrella* while north facing areas are dominated by *Picea glauca* and *Populus sp.* Wetter regions consist of *Salix* and *Alnus*. Aquatic macrophytes occupying wetlands on the surrounding shore today include: *Carex sp.*, *Scirpus sp.*, *Typha latifolia*, *Sagittaria cuneata*, *Chara*, *Potamogeton sp.*, and *Myriophyllum* (Mitchell & Prepas, 1990).

Table 2. shows some selected characteristics of Pine Lake and its drainage area, including physical parameters and water quality. Pine Lake is a well buffered lake with HCO_3^- and Na^+ as the dominant ions. Total phosphorus is probably much higher as this measurement was taken during a dry period when runoff was low (Mitchell & Prepas, 1990). Pine Lake becomes themally and chemically stratified during summer and under winter ice-cover, resulting in hypolimnetic oxygen depletion. Therefore, total phosphorus increases through internal loading during periods of anoxia. Phosphorus is high compared to nitrogen which likely favours blue-green algae.

2.2 Regional vegetation

To understand the relevance of past vegetation change, it is important to know the present distribution of plants and the major influences on vegetation zonation. Alberta is

traversed by three major vegetation zones which run NW-SE following the general course of upper westerly atmospheric flow which predominates (Fig. 1). These three zones are: boreal forest, aspen parkland, and semi-arid grassland. With the exception of the Cypress Hills, a forested upland, the grassland zone occupies the southwest corner of the province and includes wetland

Figure 1. (a.)Location of Pine Lake and other Alberta lakes referred to in this text. Vegetation zones (solid lines; Government of Alberta and the University of Alberta, 1969) and lake zones (dashed lines); Northcote and Larkin, 1963) (b) Simplified morphometric map illustrating core site locations. E= Eaglenest L; L= Lorraine L.; M= Moore L.; I= L. Isle; W= L. Wabamun; F= Fairfax L.; G= Goldeye L; B= Buffalo L.; P= Pine L.

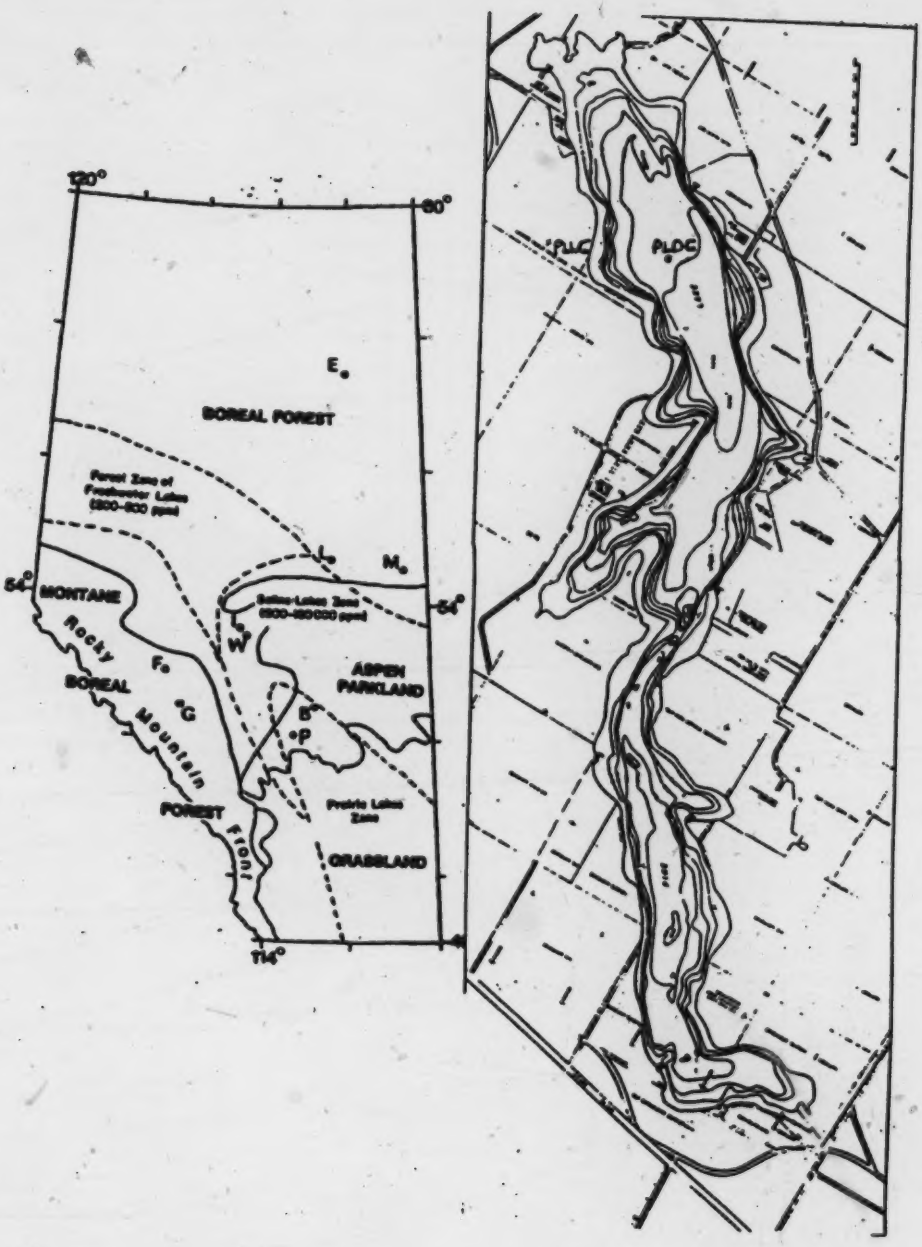

120°
60°
54°
54°
114°
BOREAL FOREST
Forest Zone of Freshwater Lakes
MONTANE
Rocky Mountain
BOREAL
FOREST
Front
ASPEN PARKLAND
Prairie Lakes Zone
GRASSLAND
PLLC
PLDC

Table. 2. Some Characteristics of Pine Lake and Drainage area

area of drainage area (km^2)	150
mean annual inflow of drainage area (m^3)	2.77×10^6
elevation (m)	889
surface area (km^2)	3.89
maximum depth (m)	12.2
mean depth (m)	5.3
shoreline length (km)	19.9
mean annual lake evaporation (mm)	640
mean annual precipitation (mm)	522
mean residence time (yrs)	9
pH(range)	7.9 - 8.9
total alkalinity (mg/L)	319
specific conductivity (µS/cm)	726
HCO_3 (mg/L)	343
CO_3 (mg/L)	23
Mg (mg/L)	25
Na (mg/L)	108
K (mg/L)	10
Cl (mg/L)	6
SO_4 (mg/L)	84
Ca (mg/L)	23
Total phosphorus (µg/L)	56

meadows, saline depressions, and dune grasslands. Plant taxa included in this zone are various grasses, Asteraceae, Fabaceae, *Artemisia* spp., *Chenopodium* spp., *Potentilla* spp., *Carex Eleocharis*, and *Selaginella densa* (MacDonald & Ritchie, 1986). Between the grassland and boreal and subalpine forests lies a transitional area called the aspen parkland where Pine Lake is located. In general, this term refers to groves of *Populus tremuloides* surrounded by low shrub and herb communities. However, *Picea glauca*, *Betula papyrifera*, *Pinus banksiana*, and *Pinus contorta* are also found in the parkland. Areas of disjunct parkland occur in the Peace River district of west-central Alberta. One can recognize an area near the northern limits of parkland called the parkland-boreal forest transition zone which contains certain coniferous elements but distinguished from boreal forest by an absence of continuous stands of spruce-birch-pine-aspen on all upland sites. The Cypress Hills are considered to be an outlier of the transitional zone with main tree species being *Picea glauca*, *Pinus contorta*, *Populus tremuloides*, *P. balsamifera*, and *Betula papyrifera*. The boreal forest can be recognized as a mosaic of closed forest stands whose composition is a function of landform, soil, and fire history. The main species found here are *Picea glauca*,. *P. mariana*, *Larix larcina*, *Abies balsamea*, *Pinus banksiana*, *Betula papyrifera*, *Populus tremuloides*, *Alnus crispa*, *Salix* , *Juniper*, ericads, various herbs and *Sphagnum*. The boreal forest may be differentiated into northern and southern boreal forest where the northern boreal forest possesses frequent tundra openings, a great predominance of conifers in forest stands, and a comparatively diminished role of deciduous angiosperms (Ritchie, 1975). The transition of southern boreal forest to aspen parkland and grassland corresponds to moderate gradients of increasing summer temperature and decreasing effective moisture (Ritchie & Harrison *in* Wright *et al.*, 1993). The subalpine forest extends from the Rocky Mountain front to the alpine treeline and is dominated by conifers. Mature stands on low elevation, well drained sites are dominated by *Picea glauca* and *Abies lasiocarpa*. *Picea engelmannii* replaces *Picea glauca* at higher elevations. Recently burned areas and lower and mid-elevations contain *Pinus contorta*. *Betula papyrifera* and *Populus tremuloides* are also present on disturbed sites. In southwestern Alberta, *Pinus flexilis*, *Pinus albicaulis* and *Larix lyalli* are important elements at treeline. A subalpine-boreal transition zone exists between the northern Rocky Mountains and boreal forest and possesses elements from both zones. Subalpine components include *Pinus contorta* var. *latifolia*, *Abies lasiocarpa* and *Picea engelmannii*. Boreal components include *Picea glauca*, *Populus balsamifera*, *P. tremuloides*, and *Betula papyrifera*.

2.3 Vegetation history of the Canadian western interior

A detailed account of vegetation the history of the western Canadian interior can be found in Ritchie, (1987) and Ritchie, (1976). Alberta was completely covered by Laurentide or Cordilleran ice until approximately 15 000 YBP and did not become entirely ice-free until 6000 YBP. It has been suggested that as ice disintegrated, ice-free surfaces and areas of till-rich stagnant ice were covered with *Picea* forest (Ritchie, 1976). This early version of boreal forest expanded northward, following melting ice sheets and was replaced along the southern margin by grassland (Lichti-Fedorovich, 1970, 1972; Mott, 1973). Pollen records from the Canadian western interior show that this early version of the boreal forest was time-transgressive, from 14 000 - 10 500 YBP at southern sites to 8 000 - 6500 YBP in the modern boreal forest (Ritchie, 1976). Records prior to this along the southern and western margin of the boreal Forest show a treeless vegetation composed of Poaceae, Cyperaceae, *Artemisia*, and at some sites, *Populus* (Ritchie, 1976; Mott, 1973; Hickman & Schweger, 1991; Lichti-Federovich, 1970). Several sites in the Pacific-Cordilleran region possess similar assemblages in late glacial sediments. These include Fairfax (Hickman & Schweger, 1991), Goldeye (Hickman & Schweger, 1993), and Toboggan (MacDonald, 1989) lakes located in the foothills of the Alberta Rocky Mountains, and several sites in northern Yukon and the North West Territories, where *Betula* was often present (Ritchie, 1987; Ritchie, 1984). It seems that this assemblage has no modern analogue and since in many cases, pollen can be identified only to the level of genus or family, it is not certain whether this assemblage is more similar to tundra or grassland-parkland regions. It is widely accepted that as spruce dominated forests moved rapidly northward, a treeless vegetation colonized areas adjacent to receding ice margins. *Picea* reached the far northwestern Canada by approximately 9000 YBP. In more southern areas spruce was replaced rapidly by grassland expansion between 11 000 and 9 500 YBP at latitudes near 52° N (Ritchie, 1976). Some evidence in more eastern areas exists that between approximately 9 500 - 6 500 YBP a narrow belt of deciduous forest separated the northern boreal forest from the southern grasslands (Ritchie, 1976). Sites located near the southern limit of the boreal forest are the most sensitive in their representation of the thermal maximum interpreted by grassland expansion (Hickman & Schweger, 1996; Lichti-Federovich, 1970, 1972; Vance *et al.*, 1983; Ritchie, 1976). The region also registers the spread of boreal forest southward between about 5500- 2000 YBP with increases in *Pinus* and *Picea* in response to a cooler and (or) moister late Holocene climate.

2.4 Regional climate

Pine Lake exists near the southern margin of the aspen parkland region and the climate for this region is characterized as continental, with short warm summers and long, cold winters (Tables 3. & 4.). Variations in temperature from summer to winter are greater on the prairies than in any other part of Canada (Hare & Thomas, 1974). Annual temperature extremes may range for the entire region from winter minimums colder than -40°C to summertime maximums close to or over 38°C (Hare & Thomas, 1974). Like the rest of the western Canadian interior, the climate of Alberta is influenced mainly by Arctic and Pacific air masses. During winter, Pacific westerlies are displaced south of the Canadian border and cold, dry Arctic air predominates. Incursions of Pacific air can occur during winter months (chinooks) and southward movement of Arctic air can bring cold temperatures to prairie provinces in all seasons. In summer months the region is affected by modified Maritime Polar or Maritime Arctic air that has crossed the Western Cordillera and become warmer and drier than it was along the Pacific coast (Hare & Thomas, 1974). Variation in yearly precipitation is typically continental with moderately heavy rain falls during the summer and very light accumulation, mostly as snow, in the winter (Hare & Thomas, 1974). Tables 3. and 4. provide available temperature and precipitation summary information at approximately five year intervals from 1899 to 1980 Pine Lake and Red Deer, respectively.

Table 3. Temperature & Precipitation Summaries for Red Deer, Alberta ND= no data

Year	Month	Temperature °C					Rain (cm)		Snow (cm)	
		Mean Max.	Mean Min.	Max	Min	Mean	Amount	Days	Amount	Days
1899	January	-6.1	-14.8	8.6	-5.3	-10.4	0.5	1	36.3	7
	July	20.9	10.2	28.5	5.6	15.6	9.0	15	0.0	0
1901	January	-4.0	-12.3	7.6	-32.8	-8.2	0.0	0	8.6	10
	July	19.8	9.7	25.4	5.6	14.7	21.9	14	0.0	0
1906	January	ND	ND	ND	ND	ND	ND	ND	ND	ND
	July	27.4	17.7	37.2	2.8	22.6	2.3	5	ND	ND
1910	January	-2.2	-18.5	9.7	-29.7	-10.4	0.0	0	25.4	2
	July	22.6	7.4	30.0	2.8	15.0	2.9	5	0.0	0
1915	January	-4.6	-19.4	5.6	-32.8	-12.0	0.0	0	24.1	4
	July	19.5	7.4	26.1	1.7	13.4	8.5	12	0.0	0
1920	January	ND	ND	5.6	-46.1	-16.1	0.0	0	50.3	7
	July	ND	ND	32.2	4.4	17.8	3.0	8	0.0	0
1925	January	ND	ND	6.7	-35.6	-13.9	0.0	0	19.8	12
	July	ND	ND	33.9	2.2	17.2	4.4	9	0.0	0
1935	January	ND	ND	7.8	-46.7	-19.7	0.0	0	42.9	11
	July	ND	ND	34.4	3.3	17.1	9.7	11	0.0	0
1940	January	ND	ND	10.6	-34.4	-14.8	0.0	0	26.7	15
	July	ND	ND	31.7	5.0	16.3	6.7	16	0.0	0
1945	January	ND	ND	6.1	-28.9	-11.4	0.0	0	14.2	9
	July	ND	ND	30.6	3.3	15.8	4.4	11	0.0	0

Table 4. Canadian Climate Normals for Pine Lake, Alberta:

Period	Mean daily temperature °F		Mean annual	Total mean monthly
	January	July	precipitation mm	rainfall mm
1941 - 1970	-14.6	15.7	485	360.8
1951 - 1980			516.6	370.6

3.0 Materials and Methods

General procedures from sediment core extraction to diagram construction are outlined in (Fig. 2).

3.1 Coring procedure

Sediment cores were collected in late March, 1994 from both the deep portion of Pine Lake's south basin and from the northeast littoral area or shore region, also in the south basin (Fig. 1). Cores, 7.6 cm in diameter were extracted with a lightweight percussion corer, using the ice cover as a coring platform (Reasoner, 1986). Duplicate cores were taken from both areas for archival reference. The Pine Lake deep core (core PLDC), was taken approximately 300 m from the shore, 11.3 m from beneath the ice surface, and measures 3.66 m in length. The Pine Lake littoral core (core PLLC), was collected approximately 102 m from shore, 4.0 m from beneath the ice surface, and measures 2.55 m in length. Water depth at coring sites was measured with the 'My Fishin Buddy II' depth finder.

After collection, cores were transported to University of Alberta where the PVC (polyvinylchloride) core barrels were sawed longitudinally with a circular saw. The sediment cores to be used were then separated into two longitudinal halves with the aid of a fine guitar string. Sediments were photographed and characterized with the aid of Munsell soil colour charts. Sedimentological description of core PLLC was provided by Mr. Rod Smith, Department of Geography, University of Alberta. Subsamples of 1 cm^3 were then removed with a plastic syringe at 5 cm intervals along the center of the core length (to avoid contamination) for loss on ignition, diatom, and pollen analysis.

3.2 Analytical methods

3.2.1 Chronological control

Identification of the tephra was done by electron microprobe analysis of glass shards at University of Alberta. Oxides of Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, S, F, and Cl were determined for 15 shards from core PLLC, sample 160cm, with an ARLSEMQ electron microbe.

Core PLDC was sieved for terrestrial macrofossils but none were found. Two woody macrofossils found in PLLC at 163cm and 234cm were submitted to IsoTrace laboratory for A.M.S. dating.

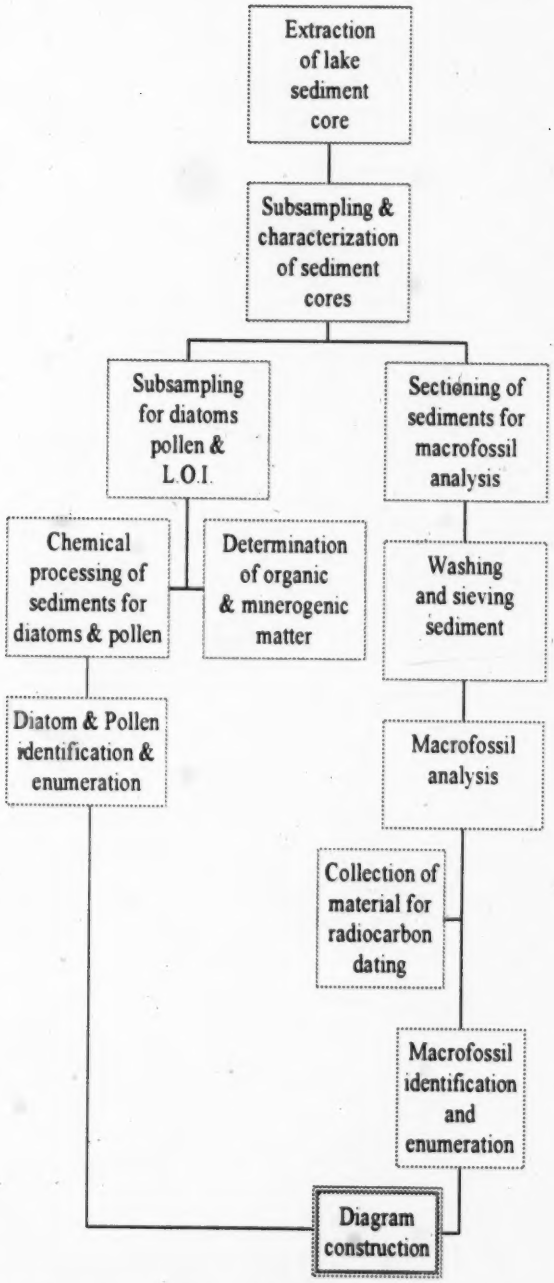

Extraction of lake sediment core
Subsampling & characterization of sediment cores
Subsampling for diatoms pollen & L.O.I.
Sectioning of sediments for macrofossil analysis
Chemical processing of sediments for diatoms & pollen
Determination of organic & minerogenic matter
Washing and sieving sediment
Diatom & Pollen identification & enumeration
Macrofossil analysis
Collection of material for radiocarbon dating
Macrofossil identification and enumeration
Diagram construction

Figure 2. Summarized scheme of analyses used in Pine Lake study

3.2.2 Loss on ignition

Loss on ignition was carried out in a muffle furnace at University of Alberta. Dry weight, percent organic matter, and percent carbonates were measured at 100°C, 550°C, and 950°C respectively, as outlined by Wetzel, (1970).

3.2.3 Pollen extraction

Sediment samples of $1cm^3$ were processed for pollen generally following Faegeri & Iverson, (1975). .Sediment samples were placed in 50 ml Nalgene centrifuge tubes and were subjected to addition of concentrated hydrochloric acid to remove carbonates. Samples were mixed well with an automatic mixer and centrifuged. Excess HCL was removed by repeated distilled water washes, each followed by centrifugation. To remove silicates, samples were treated with 20ml concentrated hydroflouric acid (HF) in a boiling water bath for one hour. HF was removed with repeated additions of distilled water and centrifugation. Sediments were found to contain great quantities of organic matter and therefore were treated with 20 ml 10% sodium hydroxide in a boiling water bath for 5 minutes, centrifuged, and washed with distilled water 3 times. To ensure samples were devoid of water, 20 ml glacial acetic acid was added, mixed well, and then centrifuged and decanted. Cellulose was next removed by acid hydrolysis, using an acetolysis mixture consisting of glacial acetic anhydride and concentrated sulfuric acid a ratio of 9:1. This mixture was placed in a boiling water bath for approximately 5 minutes. Samples were then centrifuged, decanted and resuspended in glacial acetic acid. After samples were rinsed with distilled water and centrifuged 3 times, 20 ml ethanol was added to dehydrate the samples. This mixture was centrifuged and decanted and 20 ml tertiary butyl alcohol was added, mixed, centrifuged, and decanted off. Finally, samples were transferred to 15 ml Eppendorf microcentrifuge tubes and 3-4 drops of Dow Corning® 710 silicon oil were added and mixed well with a toothpick and mounted on microscope slides.

Pollen grains were identified using the pollen reference collection of the Department of Anthropology, University of Alberta. Enumerations were carried out on a compound light microscope at 400X, while pollen identification sometimes required 600X magnification. Microscope slides were enumerated at 5 cm intervals and 300 upland pollen taxa per slide were identified and counted.

3.2.4 Macrofossil extraction

Sediments from core PLLC were sieved through 850, 425, and 212 μm mesh sizes. As recommended by Wasylikowa *in* Berglund, (1986), sampling density was adjusted according to sediment character. The assumption was made that uniform sedimentary character corresponded with minimal changes in macrofossil assemblages due to high sedimentation rate or little variation in vegetation. This assumption was found invalid and was awkward in terms of presentation of data which had to be standardized by factoring in the volume of sediment used. A regular sampling interval would have been preferable in this study. Sediment volumes were determined by the water displacement technique so that macrofossils could be expressed as number macrofossils per ml. Sediments high in clay were dispersed with Calgon® ($Na_4P_2O_7$) and gently warmed. Macrofossils were stored in water and enumerated under 75 and 150X. It is not recommended that seeds and fruits be allowed to dry as rapid and/or extensive drying will cause damage (Wasylikowa *in* Berglund, 1986). Seeds were identified according to Alexander & Barkley, 1977; Berggren, 1969; Delorit, *et al.*, 1986; Montgomery, 1977, and The Provincial Museum of Alberta reference collection. Bryophytes were identified by Dr. Bernard Goffinet and Markus Thormann, Department of Botany, University of Alberta.

It is recommended that lake sediments for macrofossil analyses be extracted from a near-shore location, where most plant remains accumulate and the core can then be correlated with others by pollen analyses (Wasylikowa *in* Berglund, 1986). Just as no plant macrofossils were uncovered from core PLDC, very little pollen was found in sediments from core PLLC after several attempts of processing to remove the abundant organic debris. For more detailed reconstruction's, a series of cores should be taken along at least two transects (Wasylikowa *in* Berglund, 1986). Although cores were taken from 3 sites along a transect from the shore towards the center of the basin, only the one core from the shore area was utilized for macrofossils. Core PLDC was sieved but no macrofossils were found and unfortunately time did not permit the analysis of a second littoral core.

3.2.5 Diatom extraction

Subsamples for diatom analysis were placed in 50 ml Nalgene centrifuge tubes and pretreated with 25 ml concentrated hydrochloric acid to remove carbonates. This was topped up with distilled water and centrifuged repeatedly until all traces of acid were gone. Organic matter was digested with a mixture of approximately 1 gm potassium dichromate and 50 ml concentrated sulfuric acid. This mixture was then washed with distilled water and centrifuged repeatedly until a pure diatom/water solution remained. The diatom slurry was topped up to 25 ml. A 0.03 ml aliquot from this volume was then placed on a circular coverslip and distilled water was added to disperse the slurry. The water was allowed to evaporate slowly to allow an even dispersion of diatoms on the coverslip. Coverslips were subsequently warmed for 1-2 hours to drive off any water remaining in the morphologically complex diatom valves, and finally mounted in Hyrax® medium.

Diatom taxonomy was determined according to: Cleve-Euler, 1951; Hustedt, 1976; Krammer, & Lange-Bertalot, 1991; Krammer *et al.*, 1985; Lange-Bertalot & Krammer, 1985; and Patrick, & Reimer, 1966. Individual diatom taxa were photographed and a total of 500 single valves were counted at X100 (oil immersion) on each slide. Chrysophyte stomatocysts were also enumerated but not included in this total. Data for individual diatom taxa are presented as relative percents. Quantitative enumeration results for the number of valves per volume per weight organic matter were determined by the following formuli:

$$N_\eta = N_c \times A/a \times V/v \times 1/\text{gm OM}$$

where N_c = valves counted in "y" fields

A = area of the coverslip
$= \pi r^2$

a = area of coverslip actually traversed (the number of fields counted x the area of just one field)

V = volume of slurry

v = volume of slurry placed upon the coverslip

gm OM = grams organic matter

N_η = the number of valves per cm^3/gm OM of sediment

3.3 Data expression

The manner in which data is presented is important to interpretation and potentially misleading if one is not properly informed. As in this study, pollen and diatom data are commonly presented as relative percentages of total count. It is therefore only possible to observe changes in taxa in relation to each other. An increase in A relative to a decrease in B may not necessarily mean that A is increasing or B is decreasing in any absolute sense. It is possible that both A and B could both be increasing or decreasing in absolute numbers, but at differing rates. Data may be expressed per unit weight but if sedimentation rate varies, changes in numbers of a certain taxon may be masked. For example, an increase in a particular species may have been accompanied by a decrease in its numbers per unit weight if the sedimentation rate increased. A more reliable method of data expression is the number of fossils per unit weight per year but this requires numerous ^{14}C dates which can be quite expensive. Only two radiocarbon dates were acquired for core PLLC in addition to the Mt. Mazama tephra correlation determined for both the PLLC and PLDC cores. For this reason sediment accumulation rates could not be calculated. Macrofossils on the other hand, are expressed as number of macrofossils/ml. This is because, although it is advantageous that macrofossils are deposited more locally than pollen, changes in macrofossil data are based upon smaller numbers than pollen. Therefore macrofossil diagrams cannot be viewed the same as pollen and diatom data which are expressed as relative percentages. Interpretation of macrofossil stratigraphy is based upon presence/absence and an increase/decrease in a given macrofossil abundance is generally interpreted as an increase/decrease in source proximity to the coring site.

Zonation was determined visually, by considering portions of the core where maximum abundances of particular taxa occurred, and comparing them to the occurrence and maximum abundance of other taxa. Zonation was very distinct, therefore statistical zonation methods were not necessary.

4.0 Results

4.1 Chronology

4.1.1 Radiocarbon analysis

AMS ^{14}C dates were obtained on the only terrestrial woody fragments found in the core extracted from the shallow site (core PLLC). The date of 8900±140 YBP at 234 cm demonstrates that the basal sediments of the core probably exceed 9000 YBP in age (Table 5.). Also provided are calibrated dates calculated from the dendro calibration data (Stuiver & Pearson, 1986).

Table 5. Accelerator Mass Spectrometry results

Sample	Material	Iso Trace Lab number	Sample Weight (mg)	Age years BP	Calibrated age years BC
PLLC 234 cm	twig	TO-5269	29	8900±140	7960
PLLC 163 cm	twig	TO-5270	6	6880±80	5705

4.1.2 Tephra analysis

Chronology was also aided by the presence of the Mazama tephra 6845 YBP. The tephra was located from 192 - 192.5 cm in core PLDC, and from 159.2 - 162 cm in core PLLC. The identity of the tephra, found in both cores was confirmed by microprobe analysis of 15 glass shards subsampled from core PLLC. The ternary diagram (Figure 3.) shows that the proportions of CaO, FeO, and K_2O for nine out of 15 glass shards, falls within the compositional range published by Westgate & Gorton, (1981). Three out of the six that are outside of the range are located in the immediate vicinity.

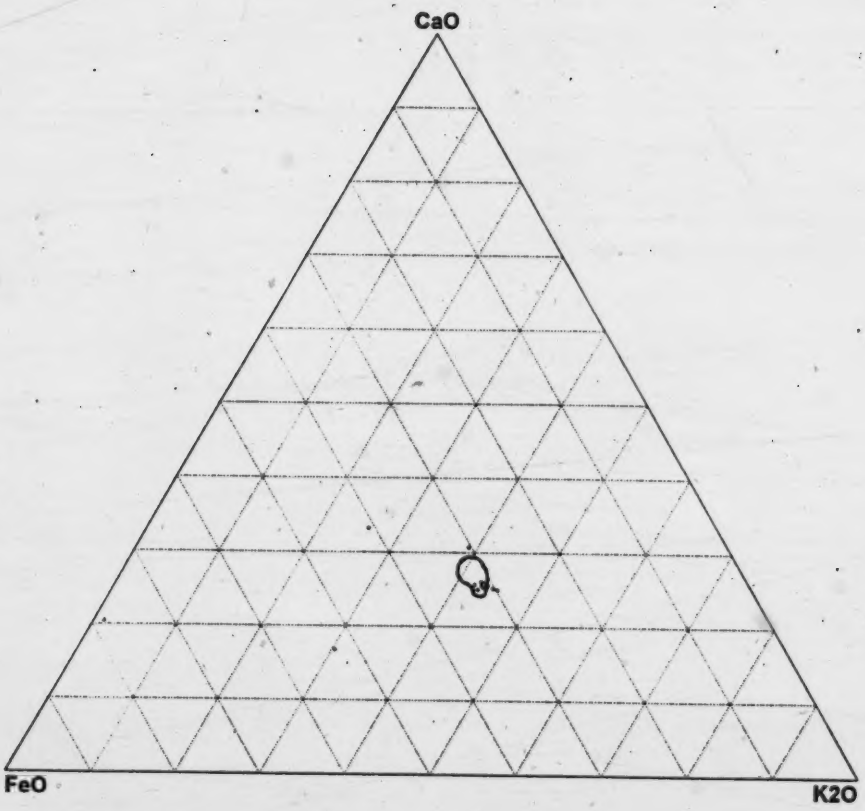


Figure 3. Ternary diagram showing relative abundance of CaO, FeO, and K_2O from sample PLLC 160. Circled area represents compositional data on the Mazama tephra according to Westgate & Gorton, 1981. Circles represent data from this study.

4.2 Sediment description

As no photographs of the cores turned out, a description using the Munsell color scheme is presented.

4.2.1 Core PLDC

Table 6. Core PLDC sediment Munsell color description

0 - 124cm	Very dark greyish brown
124 - 165.5cm	Dark greyish brown
165.5 - 168.5cm	Very dark greyish brown
168.5 - 178cm	Dark greyish brown
178 - 186.5cm	Very dark greyish brown
186.5 - 192cm	Dark greyish brown
192 - 192.5cm	MAZAMA TEPHRA
192.5- 218cm	Dark greyish brown
218 - 237cm	Very dark greyish brown
237 - 257cm	Dark greyish brown
257 - 262cm	Very dark greyish brown
262 - 272.5cm	Dark greyish brown
272.5 - 274cm	Very dark greyish brown
274 - 282.5cm	Dark greyish brown
282.5 - 285.5cm	Very dark greyish brown
285.5 - 290cm	Dark greyish brown
290 - 296.5cm	Very dark greyish brown
296.5 - 313.5cm	Dark greyish brown
313.5 - 319.5cm	Very dark greyish brown
319.5 - 339cm	Dark greyish brown
339 - 346.5cm	Greyish brown
346.5 - 348.5cm	Dark greyish brown
348.5 - 354cm	Very dark greyish brown
354 - 357.5cm	Greyish brown
357.5 - 360cm	Very dark greyish brown
360 - 364cm	Dark greyish brown

4.2.2 Core PLLC

Table 7. Core PLLC sediment munsell color description

0 - 8cm	Very dark grey
8 - 17.2cm	Dark olive grey
17.2- 24cm	Very dark grey
24-35.2cm	Dark olive grey
35.2-60.4cm	Dark greyish brown
60.4-69cm	Very dark grey
69-83cm	Very dark grey with greyish brown
83-128.7cm	Very dark grey
128.7-134.5cm	Dark olive grey
134.5-136cm	Very dark grey
136-147.5cm	Very dark grey
147.5-155cm	Dark olive grey
155-157cm	Very dark grey
157-159.2cm	Very dark greyish brown
159.2-162cm	MAZAMA TEPHRA
162-172cm	Very dark grey
172-186cm	Dark olive grey
186-191.8cm	Dark grey
191.8-196.9cm	Dark grey with creme bands
196.9-235cm	Dark grey with black bands
235-247cm	Very dark grey
247-251cm	Very dark grey
251-254cm	Dark grey
254-256cm	Very dark grey

4.3 Loss on ignition

4.3.1 Core PLDC (Fig. 4.)

Percent Organic Matter

Percent organic matter remains quite invariable throughout sediments of core PLDC. The average value for zone D1 is 23.1%. The average value for D2 is slightly higher for D2 at 24.8 %. The average percentage values for zones D3a, D3b, and D4 are 26, 26.9, and 25.7 respectively. Because such comparable values of organic matter were found throughout the massive organic silt of core PLDC, lithological analysis was not performed as in core PLLC.

Percent Carbonate

Percent CO_3 corresponds to diatom zones very closely and will therefore be described in reference to them.

Zone D1 (364 - 300cm)

Values for percent CO_3 are at their lowest in this zone with an average value of 5.8 %.

Zone D2 (300 - 225cm)

Values for percent CO_3 increase to maximum values. The average value for zone D2 is 13.7 %.

Zone D3 (225 - 140cm)

Percent carbonate continues at maximum values in D3a with an average value of 14.8 %. Values decline toward the top of D3b with an average value of 12.6 %.

Zone D4 (100 - 0cm)

The average value for zone D1 is 9.7 %. Values decline at the bottom of D1 and show a gradual rise toward the top of the zone to values of approximately 14 %.

4.3.2 Core PLLC (Fig. 5)

Percent organic matter and CO_3 values in core PLLC will also be discussed in reference to macrofossil zones.

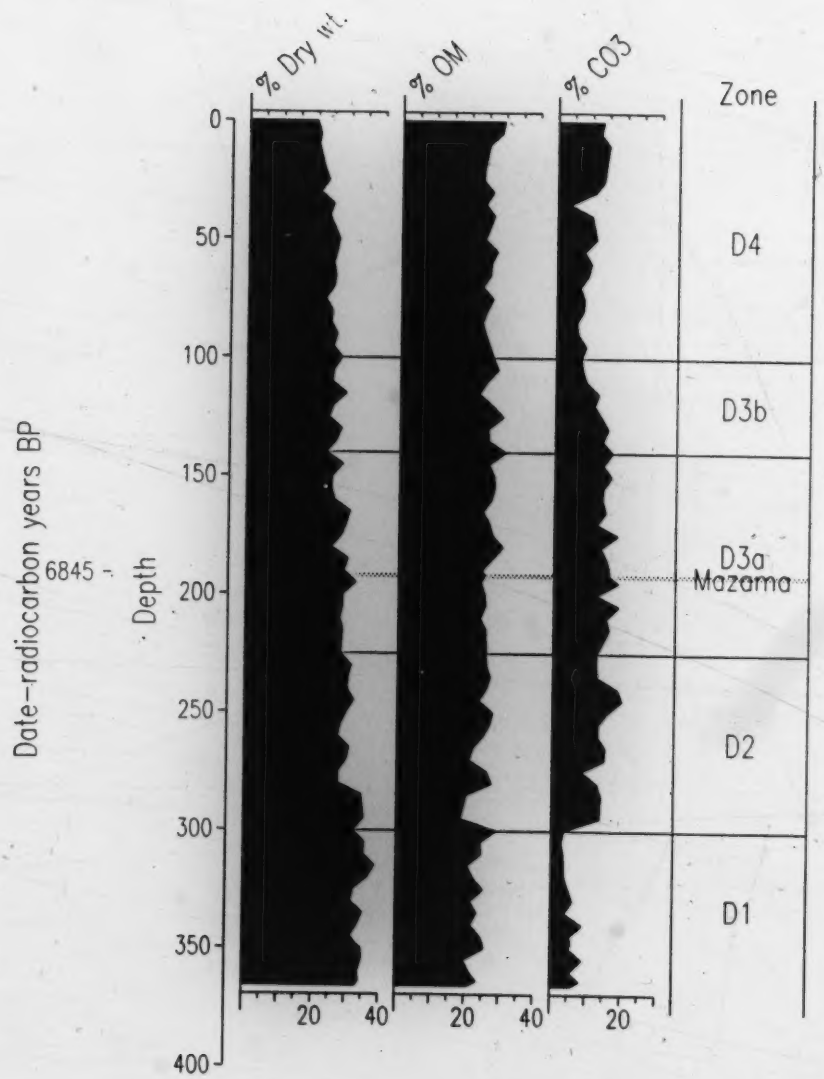


Figure 4. Core PLDC loss on ignition

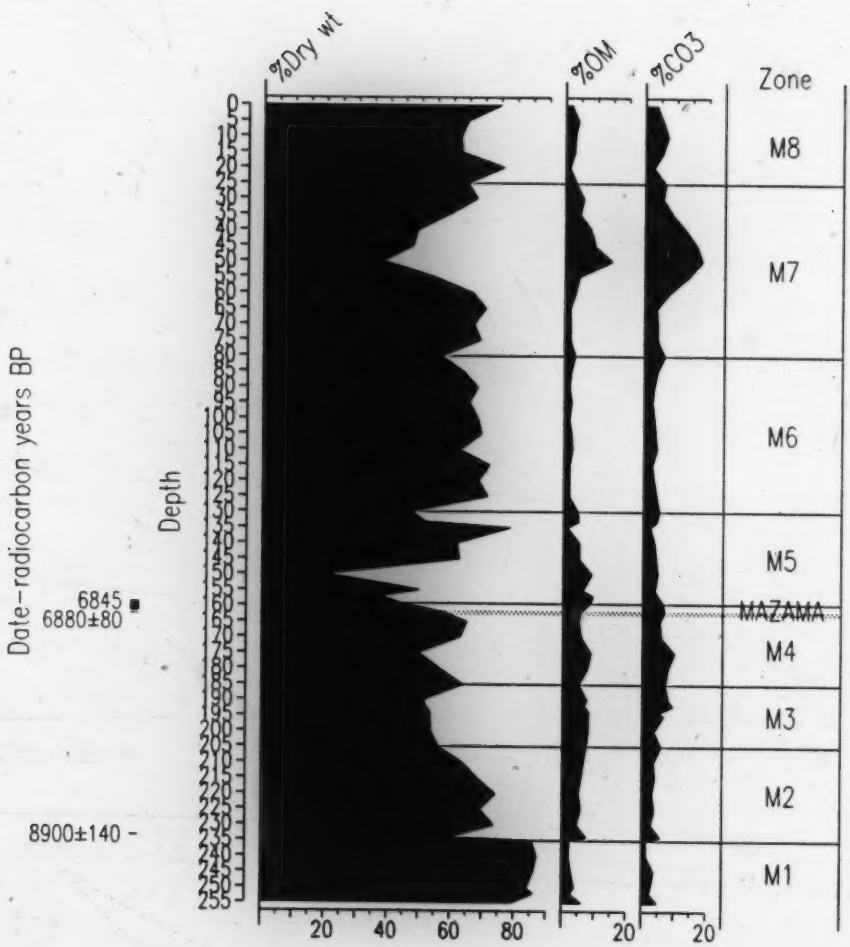


Figure 5. Core PLLC loss on ignition

Percent Organic Matter:

Zone M1 (256 - 235cm)

Values of percent organic matter are comparatively low in this zone with an average value of 3.5 %.

Zone M2 (235 - 205cm)

An increase in percent organic matter is observed with an average value of 5.5 %.

Zone M3 (205 - 185cm)

Values continue to increase with an average value of 8.0 % organic matter.

Zone M4 (185 - 162cm)

Values of percent organic matter are comparable with M3 and have an average of 6.6 %.

Zone M5 (159 - 130cm)

Percent organic matter rises at the base of this zone and then begins to decline in the upper portion. The average value for percent organic matter for this zone is 6.4.

Zone M6 (130 - 80cm)

Values show a significant decline in zone M6 with an average value of 2.3 %.

Zone M7 (80 - 25cm)

Percent organic matter shows a predominant peak at 50cm with a value of 15%. The average value for this zone is 5.5 %.

Zone M8 (25 - 0cm)

Values for percent organic matter decline with an average value of 2.7 %.

Percent Carbonate

Zone M1 (256 - 235cm)

Percent carbonate values are low with an average value of 3.2 %.

Zone M2 (235 - 205cm)

Values increase slightly to an average value of 3.7 %.

Zone M3 (205 - 185cm)

Values begin to increase at the top of zone M3. The average value for this zone is 6.8 %.

Zone M4 (185 - 162cm)

A further increase in percent carbonate is observed in this zone with an average value of 7.5 %.

Zone M5 (159 - 130cm)

Values decline in zone M5 with an average value of 4.5 %.

Zone M6 (130 - 80cm)

Percent carbonate continues at relatively low levels with an average value of 3.9 %.

Zone M7 (80 - 25cm)

A large peak in percent carbonate is observed in this zone, reaching a maximum value of 18.2 % at 50cm. The overall average value for M7 is 9.5 %.

Zone M8 (25 - 0cm)

Values decline again in zone M8 with an average value of 5.4 %.

4.4 Pollen (Fig. 6)

The data are presented in a relative percentage diagram showing major taxa (Fig. 6). Radiocarbon dates for core PLDC were not obtained, therefore pollen influx was not calculated.

Zone P1 (364 - 320cm)

Pollen in P1 is characterized by average values of *Pinus* and *Picea* of 47.5% and 14.2% respectively. *Pinus* pollen is most likely transported by wind to the site. *Alnus*, Poaceae, *Artemisia*, *Betula*, *Salix*,*Populus* and Cyperaceae occurs at average values of 9.6, 7.8, 7.7,

4.7, 3.5, 0 and 8.1% respectively. Also seen here is an unknown, designated "Ranunculaceae" which is present at an average value of 4.4%. This unknown type was tricolpate and microechinate, features typical of Ranunculaceae pollen. It also consistently

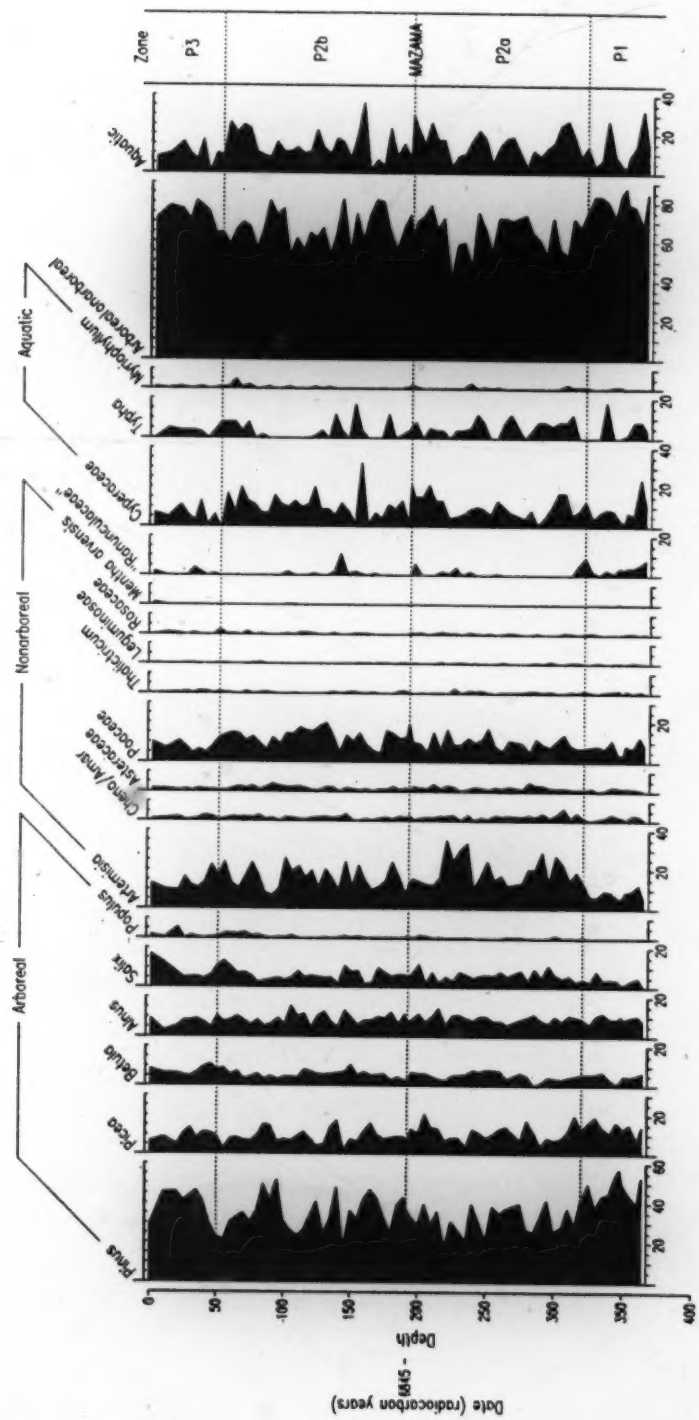


Figure 6. Pollen relative percent diagram

appeared eroded. Colpi were split open, also a feature of Ranunculaceae. Preservation of other taxa is good to excellent with the exception of sample 320 cm. This sample is categorized as "fair" as it contains several thin and torn pollen. Pyrite and charcoal are present throughout the sediment core. Because of difficulties distinguishing the two, neither were enumerated.

Zone P2a (320 - 192cm) & **P2b** (192 - 50cm)

Subzones P2a and P2b are separated by the Mt. Mazama tephra, date correlated at 6845 YBP. *Artemisia* pollen rises to average values of 19.5% while *Picea* declines to an average of 11.2% in P2a. Also in P2a, *Pinus* falls to an average value of 32%. Zone P2 is characterized by a general rise in members of Poaceae from an average value of 10% in P2a and 13% in P2b. A decline in *Artemisia* occurs in P2b to an average value of 16%. Picea also declines further in P2b to an average percentage of 8.9. *Populus* begins to rise slightly in P2a to an average of 0.2% and 0.8% in P2b. *Alnus* rises slightly to an average value of 12.7% in P2a and falls again in P2b to 9.1%. *Salix* increases 2.7% to an average value of 6.2%. Average values for *Betula* remain comparable at 5.4%. Members of Cyperaceae are in general, slightly higher in P2, reaching average values of 9.8 and 11.1% in zones P2a and P2b respectively. The ratio of arboreal to nonarboreal taxa shows a general decline in zone P2. Pollen preservation is good to very good from 315-280 cm with a few torn bisaccate grains. Preservation is fair to poor from 275-250 cm as many pollen grains are thin and torn. Preservation from 245-50 cm is good to very good with a few torn bisaccates (pollen grains possessing two bladders).

Zone P3 (50 - 0cm)

Pinus rises to an average percentage of 35%. A decline in *Artemisia*, Poaceae, and *Alnus* occur to averages of 14.1, 8.2, and 7.4% respectively. Average values of *Salix*, *Betula*, and *Populus* rise to 8.3, 7.5, and 1.1 respectively. *Populus* reaches a maximum value of 5.6% at 20 cm. Average values for *Picea* remain comparable at 9.4%. A reduction in Cyperaceae is observed with an average value of 5.7%. The ratio of arboreal to nonarboreal taxa increases. Pollen preservation from 50-30 cm is good with a few torn bisaccates present. Preservation is classified as fair from 35-0 cm as several pollen grains were torn, with abundant pyrite material inside the pollen grains.

4.5 Plant macrofossils (Figs. 7 & 8)

Lithology is discussed in reference to macrofossil zones and therefore, for the sake of simplicity, will be included with macrofossil results.

Zone M1 (256 - 235cm)

Zone M1 is characterized by variable sediment types from clayey silt at the base to various sizes of sand and silty sand. This zone is devoid of any macrofossils. Charcoal values are low with the exception of sample 252cm, which has a value of 60.

Zone M2 (235 - 205cm)

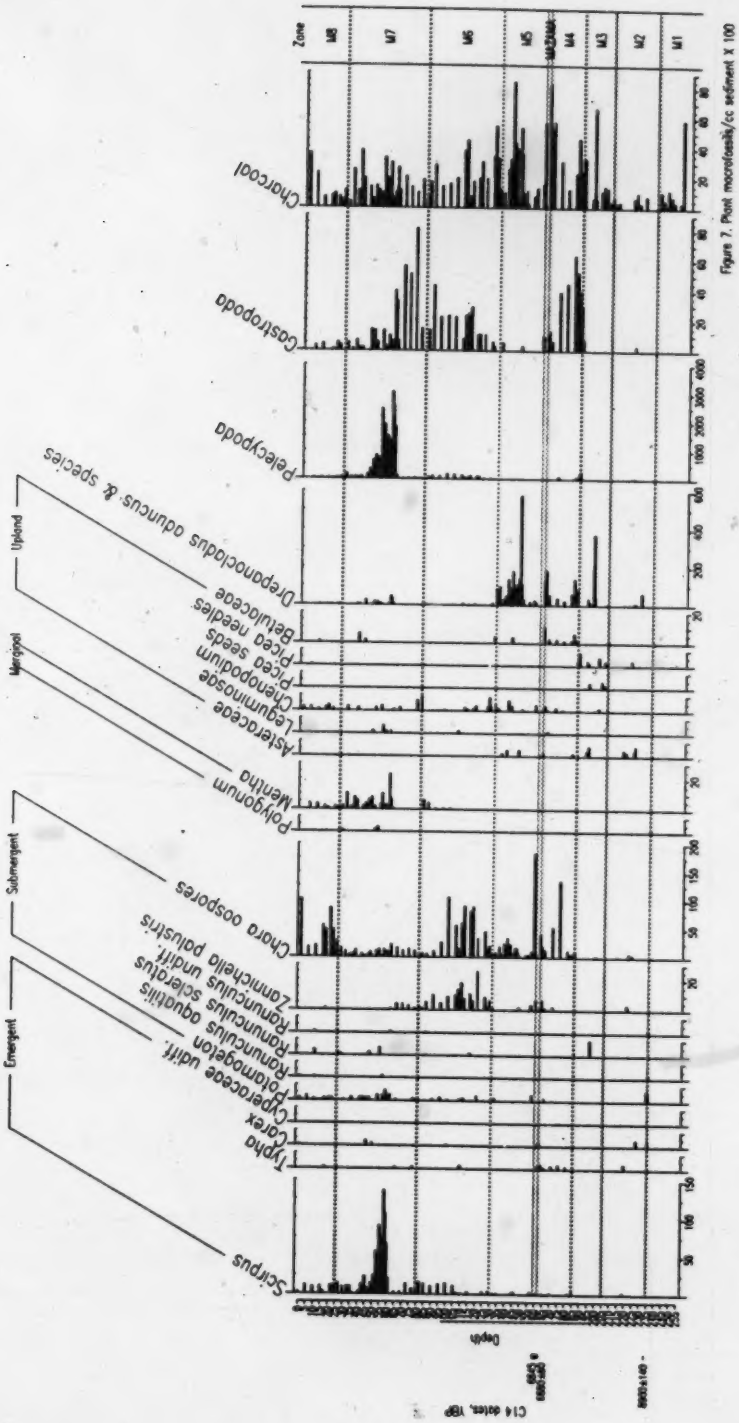
Zone M2 is composed of silty clay followed by clayey silt. Evidence of both submergent and emergent macrophytes are found including achenes of *Typha*, *Carex*, and *Ranunculus aquatilis*, *R. scleratus*, and *R.* spp., and *Potamogeton perfoliatus* druplets. These taxa are found in the 850µ fraction. Preservation is good. Although no papillae were found intact on *Typha* achenes, they were identifiable. The "beaks" of the *Potamogeton* druplets were not present. A radiocarbon date of 8900±140 years before present was determined at 234cm. Charcoal, found in both the 850 and 425µ fraction, is lowest in this zone at values of no more than 15.

Zone M3 (205 - 185cm)

A silt, sandy silt, silt sequence is found in Zone M3. Emergent and submergent aquatics disappear with the exception of *Ranunculus scleratus*. Macrofossils are comprised of *Picea* leaves and seeds which are found in the 850µ fraction. Preservation is good. *Picea* leaves are charred but retain their morphology. Identification of seeds and leaves of *Picea* alone are not possible to species level. Charcoal, found mostly in the 425µ fraction throughout the core, begins to increase in this zone.

Zone M4 (185 - 163cm)

Sediments of this zone consist of sandy silt. Seeds and leaves of *Picea* disappear and nutlets of Betulaceae and *Typha* emerge in the 850µ and 425µ fractions respectively. Preservation is fair. Wings of Betulaceae nutlets are mostly eroded. Charcoal values continue to rise, reaching a maximum at approximately 159cm. The Mount Mazama volcanic ash occurs from 159.2 - 162cm. The radiocarbon date of 6880±80 occurs at 163cm.


Zone
M8
M7
M6
M5
M4
M3
M2
M1
Charcoal
Gastropoda
Pelecypoda
Drepanocladus cf. aduncus
Upland
Betulaceae
Picea needles
Picea seeds
Chenopodium
Leguminosae
Asteraceae
Marginal
Polygonum
Menth
Chara oospores
Submergent
Zannichellia palustris
Ranunculus aquatilis
Ranunculus sclerotus
Ranunculus undiff.
Potamogeton
Cyperaceae undiff.
Carex
Typha
Scirpus
Emergent
Depth
C14 dates, YBP
Figure 7. Plant macrofossils/cc sediment X 100

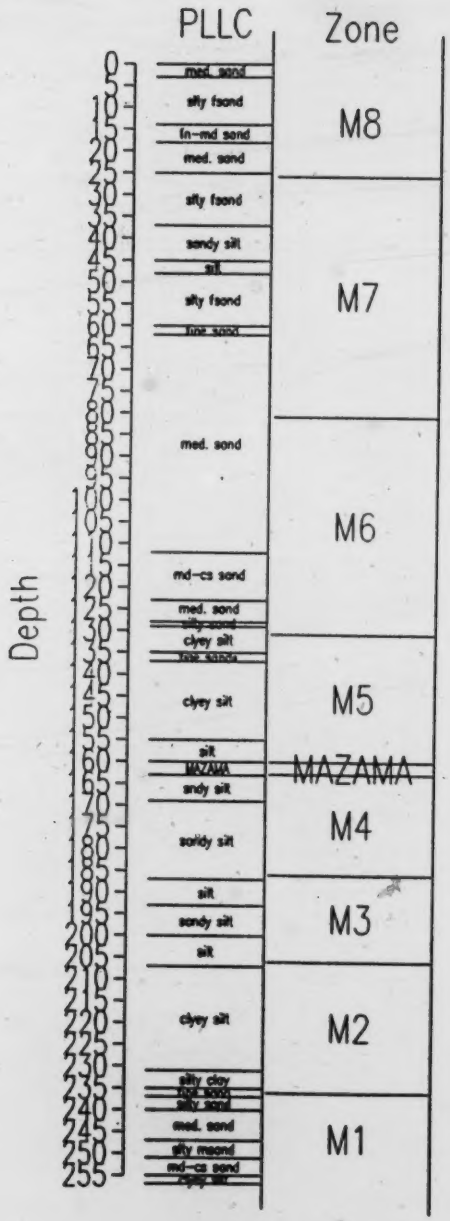


Figure 8. Core PLLC lithology

Zone M5 (160 - 130cm)

Mostly clayey silt was deposited in this zone. Betulaceae and *Typha* disappear and the bryophyte *Drepanocladus aduncus* appears. *Drepanocladus* leaves occur in the 425µ fraction while stems with intact leaves occur in the 850µ fraction. Although many leaves were detached from stems, they are not torn or frayed and therefore, preservation of *Drepanocladus* is considered good. *Chara* oospores, enumerated in the 425µ fraction, begin to increase. Charcoal is seen regularly and occurs at continually high values in the upper half of this zone.

Zone M6 (130 - 80cm).

Zone M6 is composed of medium sand. *Drepanocladus aduncus* disappears and *Chara* continues to increase in this zone. Achenes of the submergent aquatic *Zannichellia palustris* also appear and increase toward the middle of M6. Preservation is good. Charcoal begins to decline and *Scirpus* achenes begin to rise.

Zone M7 (80 - 25cm)

Zone 7 consists of a sequence of medium sand, fine sand, silty sand, silt, sandy silt, and silty sand. *Chara* and *Zannichellia* decline significantly but are still present. A sharp rise in *Scirpus validus* occurs in this zone along with increases in *Potamogeton*, and *Mentha*. As expected, *Scirpus* achenes are found without bristles intact but are in good condition. A few immature achenes were found and enumerated as *Scirpus validus*. The species of *Mentha* is most likely *arvense*, since its pollen occurs in core PLDC. Preservation is good. Charcoal shows an increase in frequency.

Zone M8 (25 - 0cm)

Sediments are characterized as medium, fine, and silty sands. *Scirpus* and *Mentha* decline significantly but do not disappear. *Chara* rises once again in this zone and charcoal abundance is reaches its lowest values. Preservation is good.

4.6 Diatoms (Fig. 9)

Zone D1 (364 - 300cm)

Pioneering benthic taxa dominate this zone. These include *Fragilaria brevistriata*, *Fragilaria construens*, and *Fragilaria construens* var. *venter*. Also present are various species of the epiphytic *Cymbella* which reach values of 15% near the base of the core. Significant numbers of the planktonic diatoms, *Aulacoseira granulata*, *Cyclotella krammeri*, *Cyclotella bodanica*, *Stephanodiscus niagarae*, and *Stephanodiscus parvus* also occur in D1. Valve concentration is at its highest. Diatom preservation is very good.

Zone D2 (300 - 225cm)

Benthic forms drastically decline here and a shift to the predominance of the planktonic, centric diatom *Stephanodiscus parvus* occurs, attaining values as high as 85%. Transition to this zone also marks the disappearance of *Cyclotella bodanica* and *Cyclotella krammeri*, and a decline in *Aulacoseira granulata* and *Stephanodiscus niagarae*. Also, *Asterionella formosa* makes its first appearance. Diatom to stomatocyst ratio is at its maximum. Valve concentration declines in comparison to zone D1 but continues to be high. Diatom preservation is very good with the exception of *Asterionella formosa*, which is found broken throughout the remainder of the sediment core.

Zones D3a (225 - 140cm) & **D3b** (140 - 100cm)

Planktonic forms continue their importance. *Stephanodiscus parvus* shows a general decline and *Aulacoseira granulata*, a filamentous planktonic form increases to values near 40% throughout zones 3a and 3b. A greater decline in *Stephanodiscus parvus* is observed in D3b to values of approximately 20%. Also declining significantly in D3b is *Stephanodiscus niagarae*. *Cyclotella bodanica* rises once again in D3b to values near 40%. The Mount Mazama volcanic ash occurs in D3b at 192cm. Diatom preservation is very good.

Zone D4 (100 - 0cm)

Planktonic forms still remain dominant here but a significant increase in benthic forms such as *Amphora pediculus*, *Fragilaria brevistriata*, *Navicula scutelloides*, and *Opephora* occurs. *Cyclotella bodanica* continues to be important although occurs more sporadically. *Aulacoseira granulata* steadily declines throughout this zone. *Stephanodiscus parvus* shows three sharp peaks throughout D4. Diatom concentration displays an increase approximately midway through this zone. Diatom preservation is very good.

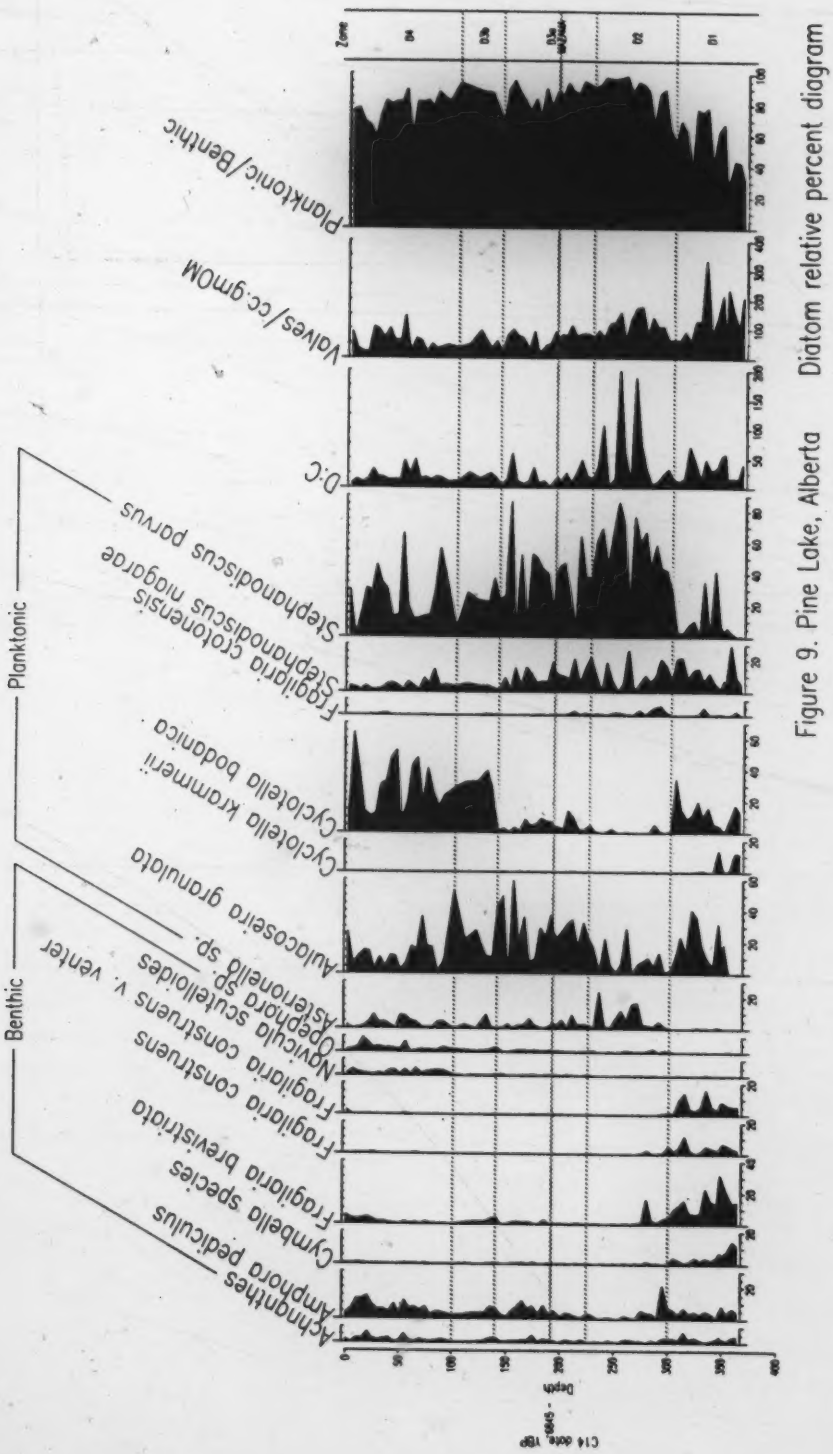


Figure 9. Pine Lake, Alberta Diatom relative percent diagram

5.0 Discussion

5.1 Loss on ignition

5.1.1 Core PLDC (Fig. 4)

Percent Organic Matter:

As mentioned in section 4.6, percent organic matter is invariable with an average value of 25.3 % for the 3.64 meter sediment core (Fig. 4). This indicates that Pine Lake has continued to be a productive lake from its inception. However, diatom production (valves per cm^3.gm.organic matter) (Fig. 9), has varied on both fine and broader scales,and suggests that the lake may have been more productive early in its development as shown in diatom zones D1 and D2.

Percent Carbonate:

Determining the cause/s of variation in the amount of carbonate in fossil sediments can be complex since there are several possible explanations. Increases in water temperature lowers the solubility of CO_2, upsetting the balance of $H_2CO_3^-$ and CO_3^{2-} and can eventually cause $CaCO_3$ to precipitate out (Wetzel, 1983). A major cause of loss of CO_2 is photosynthetic assimilation of CO_2 by phytoplankton and littoral flora. In littoral zones of hard-water lakes, submergent macrophytes become densely encrusted with $CaCO_3$ precipitated by photosynthetic utilization of CO_2 by the macrophytes and epiphytic algae (Wetzel, 1983). Precipitation of calcium carbonate is also associated with lowered water levels. Fluctuations in dry deposition of carbonate can occur with variation in runoff and eolian input of eroded carbonate rich soil. Changes in wind exposure also can vary the amount of eolian input. Mixing depth and frequency of turnover, which are affected by wind exposure, can also influence calcium carbonate deposition. Relatively cooler, more acidic waters of the hypolimnion during periods of low wind stress enhance calcium carbonate dissolution. During periods of increased mixing, temperatures of deeper waters increase, thereby decreasing the amount of dissolved carbon dioxide and increasing the pH. These conditions may lead to supersaturation and precipitation of calcium carbonate. Carbonate precipitation may also be influenced by hydrologic balance. Decreases in lake levels, groundwater influx, and surface runoff may increase the concentration of dissolved solutes and lead to their precipitation.

The percent carbonate record for core PLDC is more dynamic than percent organic matter, existing at low levels in zone D1 (Fig. 4) when algal production was relatively low and rising to maximum values in zones D2 and D3 in response to peak production of algae and

aquatic macrophytes. High percent carbonate in zones D2 and D3 may also be attributed to proposed decreases in groundwater influx and surface runoff associated with aridity. Percent carbonate values decline at the top of zone D3b and the bottom of D4 as climate cooled and production was limited. Increases in water volume during this interval would also lead to higher dissolution of carbonate. Values rise again at the top of zone D4 due to anthropogenic eutrophication and associated increases in algal production.

5.1.2 Core **PLLC** (Figs 5 & 7)

Percent Organic Matter

Comparatively low values for percent organic matter in zone M1 correspond to the absence of plant remains, hence low production of material available for decomposition. Percent organic matter increases to an average value of 5.5% in zone M2, coinciding with increases in aquatic macrophytes in the vicinity of the coring site. Further increases in percent organic matter occur in zone M3. Lake levels during this interval have declined and presence of *Picea* leaves and seeds indicate that upland vegetation has displaced aquatic vegetation zones toward the center of the lake. The source of organic matter in M3 is likely derived from both decomposition of aquatic vegetation and catchment erosion. Organic matter continues to be high in zone M4, only dropping slightly, as water levels gradually rise and aquatic vegetation growing near the core site contributes to organic matter content as well as charcoal and organic sediments from catchment erosion. As lake levels continue to increase, decomposition of aquatic bryophytes and charcoal contribute to organic matter content in zone M5. Percent organic matter drops in zone M6 as a result of water level increase and shoreline displacement toward the catchment. In this zone, organic sediments derived from the catchment are too distal to the coring site to contribute organic matter. Sources of organic matter during this interval would include charcoal and the submerged aquatics *Zannichellia palustrus* and *Chara*. A peak of percent organic matter occurs in zone M7 (40 - 55cm) approximately at the same level as the large peak of *Scirpus* (52 - 60cm) (Fig. 7). Lake levels decline during this interval, bringing shoreline closer to the coring site which would allow a

greater input of the organic component of the catchment sediments. Both the abundant achenes and rhizomatous material of *Scirpus*, incorporated into the sediments, would also contribute to the increase in organic matter. Percent organic matter declines in zone M8 as lake levels increase and shoreline is once again displaced further away from the coring site, causing a decline in deposition of organic matter derived from the catchment.

Percent Carbonate

Values for percent carbonate are comparatively low in zones M1 and M2. The increase in values toward the upper portion of M3 corresponding to a decrease in water level and possible increases in water temperature which would favour precipitation of calcium carbonate (Wetzel, 1983). Percent carbonate remains high in zone M4 while lake levels are still low. High carbonate production in this zone is also attributed to calcium carbonate precipitation associated with low water levels and high water temperatures. Also contributing to carbonate are increases in Gastropoda and *Chara*. Gastropoda are a class of the Mollusca, which incorporate calcium carbonate into their shell. The alga *Chara*, is capable of bicarbonate uptake as a carbon source for photosynthesis, particularly at high pH's (Hutchinson, 1975). In most species of Chara which live in hard waters, there is considerable precipitation of calcium carbonate on the plant's surface (Hutchinson, 1975). Values decline again in M5 with increases in water levels as well as reduction in Gastropoda and *Chara*. As lake levels increase and water temperatures decrease in zone M6, a decrease in percent carbonate occurrs although members of the Gastropoda and *Chara* oospores are present. Water levels are interpreted to have dropped significantly in zone M7, leading to the precipitation of calcium carbonate. Present in zone M7, are fruits of the emergent and submergent macrophytes *Scirpus* and *Potamogeton* which are lime-precipitating plants and therefore a source of calcium carbonate (Hutchinson, 1975). Also contributing to percent carbonate are shells belonging to members of the Molluscs, Gastropoda and Pelecypoda. Carbonate levels decline in zone M8 where lake levels are interpreted as increasing, causing dilution of the water. Although *Chara* oospores are prevalent in this zone, it is possible that the dilution effects are more important in zones M6 and M8 than the presence of calcium carbonate encrustations of the *Chara*.

5.2 The pollen record (Fig. 6)

The Pine Lake pollen record is dominated by wind-pollinated or anemophilous species such as *Pinus* and *Picea* which are potentially transported from regional sources. The contribution of pollen introduced on a particular spatial scale is a function of diameter of the lake, where smaller diameter lakes receive more local pollen and large diameter lakes receive more regional pollen (Delcourt & Delcourt, 1991). Jacobsen & Bradshaw (1981), define four source areas: local (within a 20 meter radius of the lake shore; extra-local (within the concentric zone of 20 meters to 2 kilometer radius; regional (a distance of 2 to 200 kilometers); and extra-regional (beyond a 200 kilometer radius). Pine Lake is 800 meters wide and 6500 meters long, with a surface area of 3890 m^2. According to the model proposed by Jacobsen & Bradshaw, (1981), the largest proportion of the pollen sum from Pine Lake is from regional and extra-regional sources.

Pollen representation can also vary within the lake itself. In a 1200 m surficial transect Janssen, (1966) found that the pollen input from local sources represented a very high proportion of total pollen at woodland sites but the part of the transect lying in open water was dominated by regional pollen, together with some long distance pollen (Janssen, 1966). This implies that there is a higher representation of local pollen near lake margins. Sediments from core PLLC were processed for pollen, but pollen concentration was very low. Pollen was also badly eroded and therefore, was not enumerated.

Zone P1 (364-320 cm) (early boreal forest)

The pollen assemblage of zone P1 is dominated by anemophilous *Pinus* pollen. *Pinus* produces large amounts of widely dispersed pollen and pollen frequencies close to 75% are necessary to support a vegetation reconstruction possessing more than 30% pine composition in regional forests (Ritchie, 1976). According to MacDonald & Ritchie, (1986), pollen spectra taken from modern surface samples in the aspen parkland are charcterized by 20 - 40% *Pinus*. The *Pinus* present in the Pine Lake record is mostly a result of long distance transport. High percentages of dipoxylon pine pollen from Guardipee Lake, Montana, suggest that lodgepole pine was present by ca. 12 200YBP (Barnosky, 1989). Records from the Rocky Mountains in Alberta and British Columbia show that the northern migration of *Pinus contorta* spp. *latifolia* occurred between 12 200 and 8000 YBP (MacDonald & Cwynar, 1985). It is not possible to

distinguish the pollen of *Pinus contorta* spp. *latifolia* and *Pinus banksiana*, and these two species also hybridize. For this reason, post-glacial migration history of *Pinus banksiana* is poorly understood. Suggested times of arrival of *Pinus banksiana* at Alpen Siding (54°27'; 113°00'), in the boreal forest of Alberta is 7500 YBP (Ritchie, 1975). Arrival times of jack pine in Saskatchewan and Manitoba are older in an easterly direction, suggesting a westward migration (Ritchie, 1975). Therefore, the *Pinus* species represented in zone P1 could represent either taxa.

Picea attains an average of 14.2% in zone P1. *Picea* pollen percentages for modern spectra in the parkland zone of the Canadian western interior are close to 25%. Therefore the majority of *Picea* pollen present in core PLDC is probably derived from regional sources. However, *Picea* percentages in zone P1 are higher than zones P2a (11.2%), P2b (8.9%), and P3 (9.4%), suggesting greater regional populations. The values of *Pinus* and *Picea* in zone P1 suggest that an open type of boreal forest may have been present in the area with moister areas inhabited by pine and spruce and well drained sites inhabited by *Artemisia*, (the values of which are depressed in zone P1 by *Pinus* and *Picea*). Pollen records from the Canadian western interior also show an early version of the boreal forest and it is time-transgressive, from 14 000 - 10 500 YBP at southern sites to 8 000 - 6500 YBP in the modern boreal forest (Ritchie, 1976). Times of arrival of *Picea* at Moore, Lofty, and Eaglenest Lakes, located in the Alberta boreal forest, are respectively, 11 400, 11 000-9200, and 10 700 YBP (Hickman & Schweger, 1993; Lichti-Federovich, 1970; Vance, 1985). Pollen records from a number of sites in the western Canadian interior indicate that *Betula* reached a maximum between 9500-8000 YBP and then declined between 9000-7000 (MacDonald, 1993). The pollen record of *Betula* for Pine Lake is relatively stable and shows no major declines. The percussion corer used in this study is of a relatively large diameter and during coring, resistance builds up with increasing sediment depth, preventing complete penetration. The Pine Lake record may then be missing the earliest sediments, where greater percentages of, and then a subsequent decline in *Betula* would appear. The basal date for sediments from core PLDC is therefore, between approximately 7000 and 9000 YBP. The higher percentages of *Picea* in zone P1 are then not due to migration and arrival of the taxon but a result of cooler, moister environmental conditions.

Zone P2a (320-192 cm) (*Artemisia*)

The decline in *Picea* and increase in *Artemisia* in P2a is interpreted as a shift to more open vegetation in response to early Holocene warmth and aridity. Poaceae also begins to increase and this marks a transition to grassland expansion due to fire caused by either natural or aboriginal burning.

Zone P2b (192-50 cm) (6845 - ? YBP) (grassland expansion)

In zone P2b *Artemisia* remains important, although declining somewhat from zone P2a and Poaceae pollen increases. This assemblage represents grassland expansion in response to continued but waning high summer insolation or aboriginal burning. Similar findings have been uncovered at sites located at the southern limit of the boreal forest where grassland expansion appears in early to mid Holocene records (Hickman & Schweger, 1996; Lichti-Federovich, 1970, 1972; Vance *et al.*, 1983; Ritchie, 1976).

In both zones P2a and P2b Cyperaceae pollen is generally higher, with an overall average of 10.4 % for both zones. This indicates that water levels were generally lower in these zones, exposing a greater area of the littoral zone for colonization by emergent aquatics.

Zone P3 (364-320 cm) (aspen parkland)

Increases in *Salix* and *Populus* and a general decrease in importance of *Artemisia* and Poaceae in this zone, mark the establishment of modern parkland vegetation, and the transition to cooler, moister conditions. Records from central Alberta indicate onset of a cooler, moister climate at approximately 4000 YBP, with no subsequent long term climatic changes (Vance et al., 1983; Schweger & Hickman, 1989; Lichti-Federovich, 1970).

The pollen record of nearby Buffalo Lake (53°15'N; 112°51'W) offers a comparison and is also complacent in taxa such as *Picea*, *Alnus*, and *Betula* (Hickman *et al.*, 1983). The record is not as long as that of Pine Lake and comprises a basal zone (7405 - 6760 YBP) with *Pinus* dominating to values of approximately 60 % which is not observed in the Pine Lake record. From 6760 - 3175 YBP there is a general increase in non-arboreal pollen including Cyperaceae, Poaceae, *Artemisia*, and *Ruppia* suggesting a climate with increased evapotranspiration. The Pine Lake record shares the trends in Cyperaceae and Poaceae but does not show as large an increase in *Artemisia*. The upper zone, from 3175 YBP to the present, shows a decline in *Artemisia* and *Ruppia*, and a significant increase in *Sagittaria*, as

well as *Populus* and *Salix*. This is interpreted as a shift to modern parkland conditions. The Pine lake record also shows an increase in *Populus* and *Salix* during the most recent interval.

The Pine lake pollen record exhibits a saw-toothed quality, which is a function of subsampling frequency but also reflects fine-scaled climatic perturbations, which are superimposed upon broad-scaled changes. A thorough examination requires the application of statistical analysis but preliminary visual analysis reveals trends. *Picea* and *Pinus* generally occur closely together and in either order. These are succeeded by *Artemisia* and Poaceae. *Betula* and *Alnus* follow, although they also occur with *Picea*. This follows closely to the expected sequence of invasion and adjustment following fire where pioneering herbs such as grasses and *Populus* are quickly established, followed by shrub *Betula* and *Salix* (Ritchie, 1979). In the Pine Lake record, *Populus*, which is often very poorly preserved, does not occur at high enough frequencies to allow any observation of succession. Plant species which are better competitors, such as *Picea*, usually arrive last as is the case in the Pine Lake record. The pollen of Baptiste Lake (54°45'N; 114°34'W) also possesses a saw-toothed frequency superimposed upon a relatively stable pollen record (Hickman *et* al., 1990). At Baptiste Lake, located in the boreal forest, short term perturbations such as fire are characteristic, resulting in a mosaic of vegetation at different stages of succession.

In summary, a version of a more open early boreal forest is indicated in zone P1 by the presence of *Picea* and *Pinus* in the region. More open conditions develop in response to increased warmth and aridity in zone P2 with a predominance of *Artemisia* in subzone P2a. Grassland expansion due to either natural or aboriginal burning is suggested in subzone P2b with increases in Poaceae. An overall general increase in Cyperaceae occurs in P2, suggesting lowered water levels and larger littoral area. Modern conditions are established in zone P3 with a shift to higher percentages of *Salix* and *Populus*. These broad trends are superimposed by finer scaled fluctuations in vegetation in which the succession of species suggests a response to fire.

5.3 The macrofossil record (Fig. 7)

Zone M1 (256 - 235cm)

Variation in sediment type in zone M1 may indicate fluctuating water levels during this interval, however this interval is perceived as somewhat shallower than Zone M2 which is composed of generally finer materials. It is possible that at lower water levels sediment variability would be more apparent. All lake levels fluctuate constantly due to seasonal and annual deviations from the climatic mean. When a lake stands at higher volume, short term alterations in climate would cause a smaller proportional changes in lake volume than they would if the lake were standing at a lower level (Harrison & Digerfeldt, 1993). Zone M1 is conspicuously devoid of any plant remains possibly due to turbidity caused by glacial meltwater and changing water levels, but contains some "rootlet like" material as well as charcoal. This zone represents early postglacial lake development where lake is filling but levels fluctuate. This is consistent with other records, which show that lake basins, greater than 8m began flooding long before 7500 YBP (Schweger & Hickman, 1989).

Zone M2 (235 - 205 cm) (*Ranunculus, Potamogeton*)

Zone M2 is characterized by the presence of a few emergent and submergent aquatic macrophytes such as *Potamogeton perfoliatus* and three species of *Ranunculus: Ranunculus scleratus, Ranunculus aquatilis and Ranunculus sp.*, as well as members of Asteraceae.

Potamogeton perfoliatus spp. *richardsonii* is is a submergent, rhizomatous, monocot common in waters with pH of 7.0 - 9.1and at water depths of 0.5 - 5 meters (Hutchinson, 1975). Most species of *Potamogeton* produce aerial flowering spikes which produce wind dispersed pollen (Hutchinson, 1975). The fruits of *Potamogeton* are drupe-like, with an enclosed nutlet which possesses subepidermal, air filled, lacunate tissue in the pericarp (Moss, 1983). It should be noted that seeds of *Potamogeton* are a food source for waterfowl, and therefore may be underrepresented (Birks & Birks, 1980). Also, vegetative reproduction is common in aquatic angiosperms, particularly in deep water, and several species of *Potamogeton* reproduce more freely by tubers or detached winter buds than by seeds (Moss, 1983).

Ranunculus scleratus and *R. aquatilis* are submergent, dicots. Flowers of aquatic Ranunculaceae are entomophilous, producing numerous achenes, which are also adapted for

floating and consequently may be transported a ways from their point of origin (Hutchinson, 1975). Birks, (1973), studied the distribution of macrofossils found in modern surface samples in comparison to the actual aquatic vegetation cover values in Missouri Pond. Results showed that *Ranunculus scleratus* fruits were found as far as 150 m from the shore. *Ranunculus* species may therefore be underrepresented in the Pine Lake sediments. *Ranunculus scleratus* and *R. aquatilis* are able to reproduce vegetatively by runners (Hutchinson, 1975).

Charcoal is at its lowest in frequency and abundance in this zone. This suggests that the charcoal source is further away from the coring site and/or the quantity of fuel, therefore charcoal, is less. Therefore, the lake was filling in this zone, providing habitat for submergent macrophytes, despite increasing summer insolation. Shifts in sediment type from sandy material to finer clay and silt during this interval is confirmation that lake-level was rising.

Zone M3 (205 - 185 cm) (*Picea*)

The shift to coarser materials in zone M3 corresponds to a decrease in water level. Both *Picea* seeds and needles are almost exclusive to zone M3. Evidence from zone M3 shows a clear transition from a higher water phase, where submergent macrophytes are found, to a period of increased aridity where the lake level fell and spruce trees encroached the littoral area of the lake. A general increase in macroscopic charcoal begins in this zone and extends into the beginning of zone M6. Macroscopic charcoal is considered to indicate local combustion events. Studies indicate that microscopic charcoal (5 - 80 μm) is underrepresented near the fire source because it is preferentially exported from the burn area (Clark, 1988). Therefore, the source area for microscopic charcoal is subcontintental to global and microscopic charcoal data are useful on broad spatial and temporal scales. Macroscopic charcoal (50 - 10 000 μm) is convected to lower heights on average and is deposited nearby (Clark, 1988). It therefore represents the local fire regime. Microscopic charcoal was present in the pollen slides prepared from core PLDC but was not enumerated due to the difficulty differentiating the smaller sized charcoal from pyrites. Microscopic charcoal may also look similar to very dark organic material, which was abundant in Pine Lake sediments. This increase in numbers and incidence of macroscopic charcoal in zone M3 of the Pine Lake record corresponds to the commencement of early-mid Holocene aridity. As stated earlier, stratigraphy is based upon presence/absence and interpretations of macrofossils are based upon proximity to the coring site. It is not known if charcoal production was necessarily greater during this time, (although

it would be assumed that a phase of elevated warmth and aridity would correspond to increases in fire, hence increases in charcoal) or if the increased abundance is associated with charcoal sources becoming more proximal.

Zone M4 (185 - 163cm) (Betulaceae, *Typha*)

In zone M4, lake levels begin to gradually rise as seen by evidence of *Typha latifolia* and Betulaceae. *Picea* was most likely displaced outward toward the catchment by a zone of the shrub *Alnus* (Alder) which can be found at the edge of bogs, streams, and lakes. *Typha latifolia* (cat-tail) is an emergent, rhizomatous, perennial monocot, characteristic of shallow-water marshes and wide spread in the Northern Hemisphere. Achenes of *Typha latifolia* are anemophilous and produced in late summer (Moss, 1983). Since fruits and pollen of *Typha* are wind dispersed, they may consequently be transported away from their site of production. However, in core PLLC, fruits are found in several samples throughout this zone confirming their presence locally. Evidence of *Typha* probably indicates nearby shallow water since *Typha* cannot grow in water depths of approximately 0.5 - 2 meters (Hutchinson, 1975). Macroscopic charcoal levels continue to be comparatively high in zone M4, suggesting continued aridity despite increasing water levels.

Zone M5 (160 - 130cm) (*Drepanocladus*)

In this zone Betulaceae disappears and is replaced by the aquatic moss *Drepanocladus aduncus*, which may grow from 10 cm below the water surface to 30 cm above (Gignac *et al.*, 1991). *Drepanocladus aduncus* is the only species which grows abundantly below the water surface but with maximum abundance's between 10-20 cm above the water surface (Gignac *et al.*, 1991). This species is also considered to be able to tolerate fluctuating water levels, although this information is based upon fens and not littoral areas of lakes (Gignac *et al.*, 1991). It is therefore evident that water levels are increasing further as shoreline is displaced outward. Also in this zone at approximately 135-137 cm, a very distinct sand lens is found. Macroscopic charcoal abundance is also at a maximum at this same stratigraphic level. Increased incidence of fire probably caused erosion of the catchment, leading to deposition of coarser materials in the littoral area. Surrounding lake vegetation the may have been decimated, lending to greater erosion and therefore a greater influx of material into the lake. It is not known if this is observed at other sites but is probably a significant

event. However, no meaningful interpretable shifts in the macrofossil assemblage are observed. Macroscopic charcoal is at its maximum abundances in this zone indicating continued aridity.

Zone M6 (130 - 80cm) (*Chara, Zannichellia*)

Zone M6 is characterized by increases in evidence of the submergent macrophytes, *Chara* and *Zannichellia*, which are typically found in deeper water than *Drepanocladus*, indicating a further increase in water levels.

Chara is a submerged alga, typical of hardwater and grows at 10 m or more below the water surface (Hutchinson, 1975). In very transparent water, the Characeae extend downward well below the limit of flowering plants (Hutchinson, 1975). The greatest well established depth at which any member of the group is recorded is 65.5 m, in Lake Tahoe, where *Chara virgata* occurred (Hutchinson, 1975). Most species of *Chara* produce resistant oospores in the summer and autumn (Hutchinson, 1975). *Chara* is also responsible for the deposition of marl from the conversion of lime ($CaCO_3$) and CO_2 (Fassett, 1975). Charophyceae of temperate lakes may persist as green plants well below the ice throughout the winter, when most or all of the other rooted vegetation has died out, providing winter feeding habitat for weed-dwelling animals such as Cladocera (Hutchinson, 1975).

Zannichellia is a submerged, rhizomatous, perennial, aquatic monocot. It is water pollinated (hydrophylly) and produces 4 achenes per female flower at the most (Brayshaw, 1985). *Zannichellia* typically grows in shallow (to 60 cm), often calcareous or brackish water (Brayshaw, 1985).

An increase in water depth is inferred from evidence of a shift from the shallow water bryophyte *Drepanocladus*, to the deeper water dwelling macrophytes, *Chara* and *Zannichellia*. Greater water depths and shoreward water displacement are also indicated by lowered macroscopic charcoal levels. Evidence in this zone suggests the onset of cooler, moister conditions. In the sediment record of Chappice Lake (50°10'N; 110°22'W), cooler, moister conditions are also expressed as increases in *Chara* oogonia (Vance *et al.*, 1992). However, it is not observed as a shift in aquatic vegetation zones but as an actual replacement of taxa from the saline indicator species *Ruppia* to the more freshwater indicator species *Chara*. When interpreting macrofossil and other palaeocecological data, it must be analyzed in the context of the entire record. That is, the exact stratigraphic location of each sample must

be known in relation to the whole sedimentary sequence. In the case of Chappice Lake, a shift in *Ruppia* to *Scirpus*, *Potamogeton*, *Ranunculus*, or *Typha* would indicate a reduction in salinity and probable water level increase.

Zone M7 (80 - 25cm) (*Scirpus*, Labiatae)

Zone M7 is dominated by the emergent plant, *Scirpus validus* and members of the Labiatae (Mint family). *Scirpus validus* is a rhizomatous perennial, growing in shallow water and producing bristled achenes. Jenkerson & Hickman, (1983), found *Scirpus validus* growing in Hastings Lake, Alberta between 0 and 2 meters. Dabbs, (1971), studied *Scirpus* in lakes of the estruarine plain of the Saskatchewan River and found *Scirpus validus* to never occur in more than 65 cm of water with a mean depth of 43 cm. In the core PLLC, an upwards coarsening from fine to medium sand is observed from approximately 80 - 60cm. Coarsest material appears immediately below the *Scirpus* peak. The Labiatae nutlets were not identifiable past the family level but are probably *Mentha arvense* since this pollen was identified in the top portion of core PLDC. One possible scenario is that the *ScirpusScirpus* increase denotes a decrease in water depth, since it grows in shallower water than Chara. This is supported by an associated increase in Labiatae which is marginal, indicating greater shore proximity. The upwards coarsening of sediments towards the *Scirpus* peak and the presence of comparatively coarse material near the same peak in *Scirpus* may also imply a reduction of shoreline resulting in coarser material appearing more and more proximal to the coring site. However, it also must be considered that an increase in *Scirpus* may appear during natural infilling where vegetation zones including *Scirpus*, *Potamogeton*, and *Ranunculus sp.* grow inward along with the sediment limit, toward the middle of the lake. Charcoal abundance does not increase significantly in this zone. Greater incidence of fire is expected during periods of greater warmth and aridity, therefore a higher production of charcoal would occur as long as a supply of combustible material existed. Moreover, the charcoal source would be more proximal to the coring site in the case of a lake level reduction. However, small but significant increases in *Polygonum*, Leguminosae and *Drepanocladus* occur with the peak in *Scirpus* suggesting shallow water. This evidence, when combined with increases in *Scirpus*, Labiatae, and coarser sediments, points toward a reduction in water level.

It is interesting to compare the two lines of Cyperaceae evidence. The macrofossil record shows a localized peak whereas the pollen diagram is indifferent. A similar pattern can

be seen in *Typha* fruits from zone M4 and *Typha* pollen from the pollen record. This illustrates the importance in studying macrofossil evidence in lakes, which have variable shoreline positions and undulating littoral morphometry. In such a lake, choice of a coring site is critical and a gently sloping shoreline is preferred. Cyperaceae and *Typha* fruits are deposited in the immediate vicinity of the coring site whereas pollen found in a core from the deep portion of the lake arrives from several locations from the surrounding littoral area, dampening any signal. Moreover, it would not be possible to identify *Scirpus, Ranunculus*, and *Potamogeton* as specifically from pollen evidence. In the case of *Scirpus validus*, pollen only allows recognition to family level. No pollen of Ranunculaceae could be identified for certain in this material. A badly eroded pollen type was designated as "Ranunculaceae" but the absolute identity could not be confirmed even to family level. Pollen of *Potamogeton* was not discovered either since this taxon produces pollen in very low quantities.

Zone M8 (25 - 0cm) (*Chara*)

Zone M8 spans the remainder of the core. This portion of the chronology shows a decline in the emergent *Scirpus* and a return to greater amounts of the submergent *Chara*. Charcoal abundance also declines in this zone. Hence, water levels increase during this interval due to cooler, wetter conditions comparable to that of the present, causing a shoreward displacement of macrophytic zones.

In summary, the macrofossil evidence shows that Pine Lake began filling by 8900 ±140 YBP and was deep enough for submerged aquatics to grow on shorelines. This period of rapid filling was followed in zone M3 by a reduction of shoreline as evident in increases in *Picea* seeds and leaves in response to warmth and aridity. Water levels then rose in zones M4 and M5 as shoreline zonation gradually expanded outward toward the catchment and *Alder* replaced *Picea*, followed by the aquatic moss, *Drepanocladus*. Macroscopic charcoal abundance is at its maximum during zones M3, 4, and 5, and although lake levels are rising in M4 and 5, these three zones are considered to represent the mid-Holocene aridity and correspond to pollen zone P2. Water levels must have risen significantly in response to cooler, moister conditions in zone M6 as the submergent macrophytes *Chara* and *Zannichellia* predominated. Zone M7 represents a reduction of water levels as a zone of the emergent *Scirpus* moved inward toward the middle of the lake, along with members of the mint family

(Labiatae) and a few legumes. Finally in Zone M8, as climate cooled, water levels increased to modern values as evident by the increase of *Chara* and reduction of charcoal.

Sedimentary evidence (Fig. 8), is not definitive since shifts to coarser materials do not always correspond to declining water levels. High variation of sediment type in Zone M1 probably relates to high amounts of variation in lake level and deposition of finer materials in M2 could be confirmation of shoreline expansion, but subsequent changes are less clear. A coarsening of sediments occurs at several intervals throughout the core and is not always accompanied with increased water levels. This is best illustrated in M5 and M6 where a transition to higher water levels is indicated by a shift from *Drepanocladus* to *Chara*. This shift is not associated with a change from coarser to finer sediments, but just the opposite. The sediment limit is usually defined by wind-driven currents. Therefore changes in sediment limit are not necessarily due to climate change but can be affected by variation in level of exposure caused by changes in catchment vegetation or in the type of littoral aquatic vegetation (Dearing, J.A. & I.D.L. Foster *in* Berglund, 1986). Sediment type may also be influenced by allochthonous influx due to catchment disturbance such as fire.

5.4 The diatom record (Fig. 9.)

Zone D1 (364 - 300 cm) (pioneering assemblage)

The initial diatom assemblage consists of typical pioneering benthic taxa such as *Fragiliaria brevistriata*, *Fragilaria construens*, and *Fragilaria construens var. venter*. This assemblage is recurrent among many Alberta lakes during the early Holocene and mid-Holocene in Lake Wabumun in response to reduced water levels. Members of this assemblage may be able to tolerate conditions associated with early lake development such as turbidity, low water temperature and high base status (Hickman & Reasoner, 1994; Hickman *et al.*, 1984; Hickman & White, 1989; Hickman & Schweger, 1991; Hickman & Klarer, 1981). These taxa are also found in alpine and subalpine lakes (Hickman & Reasoner, 1994), and are cosmopolitan and characteristic of alkaline lakes and ponds as well as well oxygenated water (Archibald, 1971). Primarily benthic taxa dominate zone D1 but also included in the assemblage are the planktonic forms *Cyclotella bodanica* and *Cyclotella krammerii*. These taxa are warm water stenotherms, typical of oligotrophic to mesotrophic waters (Schrader, 1979; Bradbury & Dieterich-Rurup, 1993). Its presence in Mary Lake and neighboring Lake O'Hara is correlated with warm early Holocene climates (Hickman & Reasoner, 1994). Also

present is *Aulacoseira granulata*, which has high phosphorus requirements and is therefore an indicator of strongly eutrophic conditions (Bradbury, & Dietrich-Rurup, 1993). Several species of *Cymbella* that grow epiphytically or epilithically, as well as two forms of *Fragilaria capucina*, an epiphyte upon emergent and submersed hydrophytes, are present in this zone (Hickman *et al.*, 1984). Evidence found in this zone indicates that Pine Lake was a productive lake early in its history and the basin began filling rapidly enough for planktonic diatoms to be present in significant numbers and for aquatic macrophytes to be established along shorelines as a substrate for epiphytic diatoms. This zone may then correlate with Zone M2 of the macrofossil record since a few emergent and submergent macrophytes such as *Carex*, *Potamogeton*, *Ranunculus*, and *Zannichellia* are found, indicating a rise in water levels. Absence of *Cymbella* species in all other portions of the record when macrophytes were certainly available for colonization is probably due to a reduction of water clarity and shading by both macrophytes and filamentous blue-green and chlorophytic algae which would impede epiphytic growth. The aquatic pollen record from core PLDC does not provide means for comparison and is quite unresponsive. This is expected of a lake with varying littoral morphometry, as in Pine Lake, where at a given time and lake volume, one might find populations of Cyperaceae at varying locations along the lakes edge. It could not be ascertained if the badly eroded "Ranunculaceae" pollen encountered at the base of core PLDC was such and if so, whether or not it belonged to the submerged aquatics of that family. Diatom to chrysophyte stomatocyst ratio is higher than present. Chrysophyte stomatocysts are a resting cyst produced in large numbers in response to nutrient depletion and are therefore indicative of oligotrophic conditions. High diatom to cyst ratio in this zone then possibly denotes high productivity related to high insolation already beginning at this time.

Zone D2 (290 - 200 cm) (*Stephanodiscus parvus*, high D:C)

Zone D2 shows a marked shift with the disappearance of pioneering benthic taxa as well as all of the *Cymbella* species and *Cyclotella bodanica* to a predominance of planktonic types, primarily *Stephanodiscus parvus*, which alternates with *Stephanodiscus niagarae*. Also seen is a small increase in *Fragilaria crotonensis*. Planktonic forms are at their maximum during this phase although they continue to dominate the remainder of the core with no major long term shifts. One might expect the opposite effect with benthic forms increasing due to reduced water levels and an increased littoral area but during the insolation maximum,

the photic zone probably reached significantly greater depths, allowing photosynthesis and growth of larger populations of phytoplankton.

Stephanodiscus parvus has been found to dominate the spring diatom bloom in highly eutrophic lakes in both Europe and North America (Bradbury, & Dieterich-Rurup, 1993). Its presence in the Elk Lake, Minnesota coincides with the prairie period (8.5 - 4.0 ka) and its presence may be related to periods of increased nutrient loading (Bradbury & Dieterich-Rurup, 1993). Many small species of *Stephanodiscus* prosper at low Si:P ratios and during periods of low illumination and are therefore, superior competitors in the spring (Dean *et al.*, 1994). It is then conceivable that during phase D2 silica influx from groundwater sources and runoff may have been relatively low due to aridity, allowing *Stephanodiscus parvus* whose smaller valves require less silica, to become overwhelmingly dominant. An extended period of nutrient loading due to early ice-out might also promote blooms of *Stephanodiscus parvus*. If one interprets this interval as a time of maximum aridity, then this zone corresponds well with that of zones M3 - M5 of the macrofossil diagram, (figure 7). Conversely, extended deep circulation due to cool, windy early summer could aid in phosphorus loading, leading to large blooms in *Stephanodiscus parvus*. *Fragilaria crotonensis* requires higher illumination and is a successful competitor for phosphorus and silica, and therefore, peaks later in the summer or early fall (Dean *et al.*,1994). Bradbury *et al.*, (1993), cite the dominance of *Fragilaria crotonensis* during prairie expansion in the Elk Lake record, as an indication of warm summers (high insolation) and low summer wind stress since it is known to prosper when spring circulation is weak and/or during the summer when the lake is stratified (Bradbury *et al.*, 1993). *Fragilaria crotonensis* does not dominate during this interval by any means but it reaches its highest numbers at this time and this maybe attributed to high illumination and extended periods of stratification in the late summer. The diatom to stomatocyst ratio has its maximum during this interval as well, confirming peak productivity. Alternatively, the very high D:C ratio may be an over-representation due to the relatively small size of *Stephanodiscus parvus*. This would imply that the high D:C ratio is not necessarily indicative of high productivity and D:C ratios have remained fairly constant throughout the core.

Several diatom records in Alberta show clear representations of early to mid Holocene aridity and seems to be progressively more extreme in an eastward direction. Also, according to pollen records, the timing of the thermal maximum becomes younger in an easterly direction, following the front of the waning Laurentide ice sheet (Table 1). Early to mid Holocene aridity

is manifested in a variety of ways and not simply shifts from freshwater to saline taxa. Moore Lake (54°30'N; 110°30'W), located in the southern boreal forest in east central Alberta, shows a shift from freshwater planktonic diatom taxa to saline species, namely *Chaetoceros* and *Cyclotella caspia* as well as reduced diatom production in response to changes in water chemistry (Hickman & Schweger, 1996). The pollen record of Moore Lake shows development of an open parkland/grassland vegetation at this time as well as the presence of the submersed hydrophyte *Ruppia* between 9000 and 6000 YBP indicating saline and possibly shallower water. In Lake Wabamun (53°35'N; 114°30'W), also located in the boreal parkland transition zone, mid Holocene warming and associated reductions in water level are interpreted by evidence of planktonic diatom taxa characteristic of turbid, low light environments and increases in epipelic and epiphytic taxa (Hickman *et al.*, 1984). Increases in salinity during this time are also inferred, as indicated by a large maximum of *Anomoeoneis costata* (Hickman *et al.*, 1984). Pollen correlated with this phase consists of high frequencies of Poaceae and *Artemisia* and is therefore interpreted as open prairie. Higher values of willow and sedge suggest the closer presence of a sedge fen. The presence *Potamogeton* pollen also implies lowered water levels. *Ruppia* and charcoal are also prevalent in this phase and give further evidence of aridity (Hickman *et al.*, 1984). A record from Fairfax Lake (52°58'N; 116°34'W) located in the Rocky Mountain foothills, shows that increases in benthic diatom taxa and maximum algal pigment concentrations between 9100 - 6800 YBP are related to drops in water level and associated climate change (Hickman & Schweger, 1991). At Goldeye Lake (52°27'N; 116°12'W), also in the foothills Hickman & Schweger, (1993) found both saline diatoms and then *Ruppia* pollen from 14 500 to 10 400 YBP with an intervening freshwater phase from 12 500 to 11 500 YBP. This early Holocene aridity is attributed to physical effects imparted by the existence of the Cordilleran and Laurentide ice sheets. The majority of precipitation in the Rocky Mountain region is provided by Pacific westerlies which would have been intercepted by the Cordilleran ice sheet. It is postulated that the North American jet stream was split during full glacial times (Kutzbach, 1987). One branch was diverted north of the ice sheet while the other, a stronger stream was diverted south. Pacific storms would have then been deflected south and north of the Laurentide ice sheet, away from west-central Alberta. A persistent high-pressure circulation and associated anti-clockwise winds are also predicted. This reversal of westerly flow would result in dry, warm southeasteries predominating. This, in combination with cold, dry arctic air funneled down

through the low divide between Laurentide and Cordilleran ice would result in a cool, arid environment during the late glacial.

In summary, zone D2 of the Pine Lake record, can be regarded as a time of peak aridity and diatom productivity that corresponds to the insolation maximum. During this time, long warm summers would have promoted lower Si:P ratios, early ice-out, and extended periods of nutrient loading favoring spring blooms of *Stephanodiscus parvus*. At the same time, longer periods of stratification allowed for presence of *Fragilaria crotonensis* later in the season.

Zone D3 (200 - 140 cm) (*Aulocoseira granulata*):

Zone D3a marks the transition from a predominance of *Stephanodiscus parvus* to increases of, and alternations with *Aulacoseira granulata*, as well as the appearance of Mount Mazama volcanic ash (6845 YPB) at the base of the zone. The planktonic taxon *Aulacoseira granulata* is a indicator of strongly eutrophic conditions. As well as phosphorus, *Aulacoseira* has high requirements for silica to support its robust valves (Kilham, P., 1971). Its abundance, therefore may then indicate higher silica influx via groundwater and/or surface runoff due to increased precipitation. According to Bradbury *et al.*, (1993), *Aulacoseira granulata* characterizes low light environments which could be a result of turbidity associated with increased precipitation. *Aulacoseira granulata* reaches its maximum during the summer and requires turbulent mixing for maintenance of suspension (Lund, 1954). Persistence of high insolation during this interval would permit a deeper photic zone, allowing *Aulacoseira* to proliferate. It is interesting to note that percentages of *Aulacoseira* alternate with those of the very fragile *Asterionella formosa*, which preserves poorly under turbulent conditions. The general increase in *Aulacoseira granulata* probably coincides with increased windiness and silica influx coupled with continued high insolation, shown by the persistence of *Stephanodiscus parvus*.

Cyclotella bodanica appears in zone 3b. This taxon is indicative of oligotrophic to mesotrophic water but is considered somewhat opportunistic (Schrader, 1979). It also requires large quantities of silica, therefore, confirms continued increases in moisture.

Cycotella bodanica appears in sediment records of several Alberta and British Columbia lakes and its ecological tolerances are fairly well known. The variety of palaeoecological information that may be extracted from its abundance differs, depending upon

the other diatom taxa preceding and coexisting with *Cycotella bodanica* as well as particular characteristics of the lake itself such as chemistry, nutrient status and sediment type. In the sediment record of subalpine Mary Lake (51°21'N; 116°20'W) in nearby British Columbia the closely related species, *Cyclotella radiosa* was prevalent in the lake between 10 000 and 5000 YBP corresponding to the hypothesized warmest period based upon the pollen record (Hickman & Reasoner, 1994). This was the only planktonic species present and is considered to be a warm water stenotherm, and since many planktonic species require water temperatures of 10°C, its abundance was linked to climate change. *Cyclotella radiosa* occurs in the diatom record of Baptiste Lake (54°45'N; 114°34'W) and its appearance is coincident with lower epilimnetic nutrient levels due to incomplete mixing when temperatures were warmer than present (Hickman *et al.*, 1990). As temperatures decreased to modern values, a marked shift from laminated sediments with *Cyclotella radiosa* to unlaminated sediments with the phosphorus loving species *Aulacoseira granulata* occurred. In the record of Fairfax Lake (52°58'N: 116°34'W), a shift from benthic taxa to rises in planktonic the species *Cyclotella radiosa* along with *Aulacoseira ambigua* and *Tabellaria fenestrata*, are related to rising water levels coinciding with changing climate and increasing amounts of precipitation (Hickman & Schweger, 1991).

In the Pine Lake record, both *Aulacoseira granulata* and *Cyclotella bodanica* peak during the summer months. The coexistence of the two may imply that they have slightly different growth seasons or more likely that *Cyclotella bodanica*, although commonly found in oligotrophic waters, is quite capable of successful growth in eutrophic conditions.

In summary, the increase of relative percentages of *Aulacoseira granulata* in subzone D3a reflect increases in moisture although high insolation persists during this time as shown by the continuing dominance of *Stephanodiscus parvus*. In zone D3b, *Stephanodiscus parvus* decreases in importance and *Cyclotella bodanica* appears and is codominant with *Aulacoseira granulata* suggesting further cooling and increases in moisture.

Zone D4 (140 - 0 cm) (>Benthic:Planktonic)

Diatoms in this most recent interval display a shift in importance of benthic taxa such as *Amphora pediculus*, *Navicula scutelloides*, and *Opephora martyi*. *Amphora pediculus* is an epiphyte in well aerated, shallow water or in the current. This epiphyte occurs mostly on filamentous algae or large diatoms (Patrick & Reimer, 1966). Several filamentous algae have

been reported to presently grow in Pine Lake (Watson, 1993). Following early spring, the phytoplankton community is dominated by filamentous cyanophytes *Aphanizomenon flos-aquae* and *Anabaena lemmermanii*. Near shore surface scums, prevalent during mid-summer were collected and were found to include the filamentous chlorophytes, *Spirogyra* and *Ulothrix*. Therefore, *Amphora pediculus* is probably living epiphytically on one or more of these species. *Navicula scutelloides* is common on calcareous sediments (Patrick & Reimer, 1966). The increase in this epipelic species is probably due to infilling of the lake and an increase in the sediment limit.

Cyclotella bodanica and *Stephanodiscus parvus* continue to be important taxa in this zone. It is interesting that *Aulacoseira granulata* and *Stephanodiscus parvus*, which are strong indicators of eutrophic conditions, were more predominant during the mid-Holocene aridity than in more recent times. Pine Lake is adjacent to feedlots and is frequently subject to input of septic tank overflows during springtime from surrounding cottages and resorts. While *Aulacoseira granulata* and *Stephanodiscus parvus* are important taxa in zone D4, they may be subject to competition with Cyanophytes.

In summary, presence of planktonic and epiphytic diatoms in zone D1, suggest that the lake was already filling rapidly at this time. Diatom to cyst ratio and diatom concentration also indicate that Holocene warming was already having an effect. If the scenario involving shifts in Si:P ratios in response to altered lake levels and associated changes in diatom taxa is true, then the brief transition within zone D1 of the diatom record from pioneering benthic diatoms to the highly silicified *Aulacoseira granulata* and *Cyclotella bodanica*, could be interpreted as a short period of higher precipitation. This wet period then corresponds with that of zone M2 of the macrofossil diagram (8900 YBP- ?) where a phase of relatively high water levels, indicated by fruits of both emergent and submergent aquatic plants, is followed by a significant drop in lake level, indicated by the appearance of *Picea* seeds and needles. An interval of higher effective moisture has also been found at Toboggan Lake (50°46'N;114°36'W) as indicated by rises in *Picea* percentages and accumulation rates to a maximum between approximately 9400 - 8400 YBP (MacDonald, 1989). It is speculated that the early period of aridity was similar to that experienced by the Pacific northwestern United States where subtropical Pacific high pressure systems, amplified by increased insolation, blocked incursions of moist Pacific airmasses. The second period of aridity would then be

caused by persistent, increased insolation and warm dry southerly flows. One can compare this with evidence found in Moore Lake, Alberta (54°30'N; 110°30'W) where a freshwater interval (9100 - 8400 YBP) as indicated by freshwater diatoms, interrupts a longer saline period (9000 - 6000 YBP), as indicated by *Ruppia* and saline diatom taxa (Hickman & Schweger, 1993; 1996). The size of the freshwater response found in Moore Lake suggests that the event is valid, and not the result of sediment redistribution since the sediments are laminated (Hickman & Schweger, 1996). Of course the Pine Lake record is not as long as that of Moore Lake, which spans from nearly 12 000 YBP, and it is not possible to observe whether conditions were more arid prior to zone M2 (8900 YBP). As mentioned previously, zone M1 is essentially devoid of any macrofossils except for one sample at 254 cm with abundant charcoal counts. However, it is not possible to determine whether lake levels were lower in this zone since in this early phase of the lake's history, aquatic macrophytes may not have been able to colonize the mainly inorganic sediments. The diatom record of Pine Lake also differs from that of Moore Lake in that Pine Lake has never been saline and therefore, would show no saline/freshwater transitions. Nonetheless the Pine Lake diatom record does show an increase in planktonic taxa in zone D1 which may correspond to zone M2. The actual cause for this moister/cooler episode among the three sites is uncertain and since the sites are from different regions of Alberta and were probably under different climatic restraints, this can only be viewed as coincident.

Following zone D1, continued increasing aridity is shown in D2 by increases in the tiny *Stephanodiscus parvus* which is capable of proliferation under the silica stress caused by decreased groundwater levels and surface runoff. Diatom concentration is comparatively high in this zone as well as D:C, which is at a maximum.

Increases in the robust diatoms *Aulacoseira granulata* and *Cyclotella bodanica* in D3 indicate increased silica influx associated with rising water levels and a cooler, moister climate. Greater numbers of *Aulacoseira granulata* may also occur due to increase in depth of the photic zone. Finally, increases in benthic forms in D4 probably relate to natural infilling and the predominance of other filamentous algae providing a suitable substrate. Reduction in relative percentages of the eutrophic indicator *Aulacoseira granulata* suggests an increase in competition for phosphorus from filamentous green and bluegreen algae. The oligotrophic to mesotrophic indicator *Cyclotella bodanica* is able to dominate zone D4 since it has lower phosphorus requirement.

6.0 Synthesis (fig.10)

The pollen, macrofossil, and diatom records of Pine Lake are shown to be sensitive indicators of climate change. Each possesses the ability to register climatic shifts on different temporal and spatial scales and are manifested by each in unique ways. Early to mid-Holocene aridity is shown by all three records. Fig. 10 is a summary diagram showing pollen, macrofossil and diatom zones and their possible correspondence to each other.

The pollen record evidence is derived from regional sources and represents more general climatic trends. Early in the record in zone P1, predominance of *Pinus* and *Picea* provide evidence of presence of a version of early boreal forest. The pollen assemblage of zone P2a registers conditions of warmth and aridity in the form of more open vegetation with higher percentages of *Artemisia*. Grassland expansion occurs in zone P2b in response to either natural or aboriginal fire. Increases in *Salix* and *Populus* in pollen zone P3, mark the development of modern parkland vegetation. The saw -toothed nature of the pollen record reveals a fairly consistent pattern in vegetation succession composed of a herb - shrub - tree cycle. This suggests that vegetation is responding to a small -scale disturbance such as fire.

The local nature of the macrofossil evidence provides information about environmental changes occurring within the shoreline region of Pine Lake. The record of climatic change is provided in the form of modifications in shoreline, which are reflected in shifts in vegetation zonation. Macrofossil zone M1 is devoid of macrofossils but M2 contains evidence of both emergent and submergent macrophytes. Zones M2 and M1 possibly correspond to pollen zone P1. Water levels drop in zone M3 with the replacement of aquatics by *Picea* and increased charcoal, signaling the beginning of mid-Holocene aridity. Water levels gradually increase in zones M4 and M5, as *Picea* is replaced by the shrub *Alnus*, followed by the aquatic bryophyte *Drepanocladus*. Charcoal levels continue to be the greatest during zones M3, M4, and M5 suggesting continuation of arid conditions despite gradually increasing water levels. Macrofossil zones M3, M4, and M5 indicate mid-Holocene warmth and aridity and correspond to pollen zone P2. *Chara*, present in macrofossil zone M6 indicates a significant increase in water levels associated with a moister, cooler climate. This zone then corresponds to pollen zone P3. Two episodes appear in the macrofossil record and are not evident in either diatom or pollen records. These include the discrete sand lens and increased charcoal at 135 cm in the littoral core suggesting that fire in the surrounding catchment caused increased erosion. Also observed is a reduction in water level in zone M7 reflected by increased *Scirpus*. Water levels

Pollen

Dominant taxa	Interpretation
Salix, Populus P3	Modern aspen parkland cooler, moisture conditions
Poaceae, Cyperaceae P2b	Grassland expansion due to natural or aboriginal fires.
Artemisia, Cyperaceae P2a	More open vegetation increased warmth and aridity. Increased littoral area due to decreased lake levels and an associated increase in littoral area. (Subzones P2a & P2b)
Picea , Pinus, Alnus P1	Early version of an open boreal forest

Diatoms

Dominant taxa	Interpretation
Amphora pediculus, & other various benthic forms. *Cyclotella bodanica, Stephanodiscus parvus* D4	Increased sediment limit caused by sediment infilling, providing larger littoral area for benthic forms. Diatoms growing epiphytically on other filamentous algae. Competition with cyanophytes
Aulacoseira granulata & *Cyclotella bodanica* D3b	Continued transition to moister cooler conditions
Aulacoseira granulata Stephanodiscus parvus D3a	Increased precipitation and associated increase in Si influx Photic zone still deep.
Stephanodiscus parvus, Fragilaria crotonensis maximum D:C, high diatom valve concentration D2	Peak warmth and increased depth of photic zone. Extended period of nutrient loading due to early ice-out Lowered Si influx due to decreased surface runoff and groundwater input.
Fragilaria brevistriata, F. construens, Cymbella species *Aulacoseira granulata, Cyclotella bodanica* D1	Pioneering assemblage Planktonic taxa indicate lake was filling rapidly

Macrofossils

Dominant taxa	Interpretation
Chara, lower charcoal abundance M8	Cooler, moister conditions of the present
Scirpus, Mentha, Drepanocladus, charcoal increase M7	Significant reduction of lake level. Increased aridity.
Chara charcoal declines M6	Significant increase in water level. Cooler, moister conditions.
Drepanocladus aduncus charcoal M5	Further increase of lake level. Continued aridity
Betulaceae, *Typha*, charcoal M4	Gradual increase of lake level. Continued aridity
M3 *Picea*, charcoal	Reduction of water level. Warmer, more arid
Emergent & submergent hydrophytes M2	Increase in water level
High variation in sediment type M1	Fluctuating water levels

Figure 10. Pollen, diatom, & plant macrofossil summary diagram

increase again in zone M8 with the replacement of *Scirpus* with a predominance of *Chara*. Zones M7 and M8 also correspond to pollen zone P3.

Climatic changes are manifested in the diatom record as shifts in dominant diatom taxa in response to climate induced fluctuations in silica and depth of light penetration. The initial diatom assemblage of diatom zone D1 is composed of typical pioneering benthic species as well as planktonic forms. This indicates that the lake, which had begun filling, was already deep enough to support significant numbers of planktonic diatoms. Zone D1 corresponds to macrofossil zone M2. One could possibly include zone M1 with M2, as also corresponding to zone D1 but it is difficult to interpret lake level conditions in M1 since no macrofossils were found and dates for both cores are not available. Maximum aridity is suggested in diatom zone D2, where the tiny *Stephanodiscus parvus* dominates, indicating lowered silica:phosphorus caused by a reduction in groundwater influx and surface runoff. *Stephanodiscus parvus* remains important in subzone D3a but the robust, planktonic form *Aulacoseira granulata* increases in importance, suggesting that although insolation is still high, climate is cooling and with moisture increasing, inputs of silica into the lake are higher. Diatom zone D2 corresponds to pollen zone P2 and macrofossil zones M3, 4, & 5. A transition to cooler, moister begins in diatom zone D3 with an increase in relative percentages of the robust diatoms *Aulacoseira granulata* and *Cyclotella bodanica*. Both diatom and macrofossil evidence possibly show a wet interval that interrupts the early Holocene warm period.

7.0 Conclusions

This investigation effectively demonstrates that together, the three lines of evidence: pollen , macrofossils, and diatoms, provide corroborative evidence of broad climatic changes as well as smaller scale, individualistic responses. Pollen data reflect regional climatic fluctuations, superimposed by finer scaled perturbations. These serve as a comparison of the regional, terrestrial record with that of the local environment of the lake and its catchment. Plant macrofossil data demonstrate the strong ability to monitor climatic change in the local environment. The diatom data show clear evidence of environmental change. Indications of climate change are afforded indirectly, through evidence of climate related nutrient changes. These data also demonstrate the sensitivity of sites located at the southern boundary of aspen parkland.

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